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FACULTY OF SPORT, EDUCATION AND SOCIAL SCIENCES

Biomechanical Analysis of Flatwater Sprint Kayaking

by

Mathew Ben Brown

Thesis for the Doctor of Philosophy

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ABSTRACT

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Flatwater sprint kayaking performance can be assessed through the analyses of average boat velocity a paddler can produce, which has been shown to be directly linked to the levels of force production. Furthermore kayaking has been the subject of substantial level of investigation, within which research has identified that the evolution of equipment and resultantly technique has a direct effect on performance. The focus of the previous research has revolved around the upper limbs, with the trunk and lower limbs viewed as an inconsequential base around which the upper limbs move. Therefore the current thesis attempts to identify the application of the entire body during kayak paddling and clarify the importance of trunk and leg contributions to performance. A notational analysis of technique was conducted comparing novice, national and international level paddlers. International paddlers displayed significantly ($P < 0.05$) lower race and stroke times, as a result of significantly higher stroke rates. In addition aspects of technique were ranked from zero to five from which international paddlers displayed significantly ($P < 0.05$) greater trunk rotation, leg motion, stroke width, and forward reach. These findings were supplemented by the international paddlers entering the paddle significantly closer to the centre line of the kayak, while holding a fixed forward lean position of the trunk. These findings provide important factors within technique that can be identified visually; however further investigation was required to identify their importance in the development of force and kayak velocity. Consequently the development of an on-water analysis system was required to ensure a comprehensive analysis of technique. This was conducted through the combination of kinetic, 3-demensional kinematic, electromyographic and electrogoniometric analysis methods, using subjects (n = 8) with international experience. Subjects were prepared with passive surface electrodes and joint markers, and completed the testing protocol following completion of informed consent and a medical questionnaire. Statistical analysis identified that a moderate positive significant predictive relationship ($R^2 = 0.529$, $P < 0.05$) existed between peak force and mean velocity during the left paddle stroke. Separating the trunk into thoracic and lumbar regions revealed a significant negative predictive relationship ($P < 0.05$) between velocity and range of lumbar spine rotation. Further significant ($P < 0.05$) findings were identified between activation levels of the rectus abdominus, external obliques and the production of force and velocity. The combination of these findings indicated that the lower trunk acted as a strong stable base against which force was produced increasing average kayak velocity. The activation of the left rectus femoris displayed significant relationships ($P < 0.05$) with force and velocity during both left and right strokes; indicating that the legs act braces against which the force is transferred to the kayak. These findings reinforced those identified during the notational analysis, indicating that the legs and trunk play a fundamental role within the development of kayak velocity and therefore performance. It is therefore important that paddlers ensure that the musculature of the trunk and legs are used during performance and that the vital axial rotations occurring in the spine are produced in the thoracic region.

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Declaration of Authorship

I, Mathew Ben Brown declare that the thesis entitled Biomechanical Analysis of Flatwater Sprint Kayaking and the work presented in the thesis are both my own, and have been generated by me as the result of my original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at the University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated;
- Where I have consulted the published work from others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I acknowledge all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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  Brown, M.B., Lauder, M., and Dyson, R. (2007) Analysis of skill level in flatwater kayaking, In the *Proceedings of the 12th Annual Congress of the European College of Sports Science, Jyvaskyla, Finland.*

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Date: ....01 - 07 - 2009..........

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1. Introduction

1. 1. Development of the sport of kayaking

The sport of competitive kayaking first came to prominence in the early part of the 20th century with its inclusion in the 1924 Paris Olympics coinciding with the formation of the International Representantskapet for Kanotidrott (IRK). However, it took a further 12 years before the sport was given full Olympic recognition with inclusion as a medal sport for the first time in the 1936 Berlin games, with both single and two man events over 1000 m and 10000 m of flat-water, in solid and folding boats. Following the games the outbreak of the second world war changed the sport as a result of allied bombing destroying the headquarters of the IRK. In 1946 the IRK was reformed becoming the International Canoe Federation (ICF), that continues as the international governing body for the sport today.

Within the ICF the range of disciplines undertaken today by paddlers has changed to include white water, slalom, rodeo, surf and flat-water. It is the final discipline, flatwater kayaking, that is the main interest of this thesis. A range of events now exist from short sprint races of 200 m and 500 m to 1000 m and 10,000 m and marathon distances. In addition there are relay races that take place over 200 m and 500 m. The number of competitors in each boat has also changed, with singles (K1), pairs (K2) and quads (K4) competing in all events for both men and women. The competition times for the races vary greatly with the greater the number of crew the lower the times as shown in table 1.1.

Table 1.1. Times for the winners of events at the Athens 2004 Olympic games.

Distance (m)	Event	Gender	Time (mins:secs.msecs)
500	K1	Male	1:37.919
	K2	Male	1:27.040
	K1	Female	1:47.741
	K2	Female	1:38.101
	K4	Female	1:34.340
1000	K1	Male	3:25.817
	K2	Male	3:18.420
	K4	Male	2:56.919

The physical requirements for each event differs with the long distance races (1000 m and greater) requiring large aerobic capacities (Csende *et al.*, 1998). Maximal oxygen uptake ($\dot{V}O_2max$), defined as the ability of an athlete to intake, transport and utilise oxygen during exercise and measured in either litres per minute or millilitres per kilogram of body mass per minute. Some research reports $\dot{V}O_2max$ values as high as 5.39 ±0 .44 $L.min^{-1}$ or 61.9 ±2.9 $ml.kg^{-1}.min^{-1}$ for males and 3.97 ± 0.30 $L.min^{-1}$ or 53.3 ± 7.0 $ml.kg^{-1}.min^{-1}$ for females (Sitkowski, 2002). When considering race times as a tool of comparison, similar times can be identified in the 500 m K1 and an 800 m track race (1:43.83 mins) and in the 1000 m K1 and the 1500 m track race (3:31.96 mins) (Conley *et al.*, 1984; Daniels and Daniels, 1992:). However, when considering the latter case the $\dot{V}O_2max$ values for elite males differ with 800 m values reported to be 72.1 $ml.kg^{-1}.min^{-1}$ (Daniels and Daniels, 1992) and 1500 m values of around 5.85 $L.min^{-1}$ or 80.1 $ml.kg^{-1}.min^{-1}$ (Conley *et al.*, 1984), whilst the kayakers presented values of 5.39 ± 0.44 $L.min^{-1}$ or 61.9 ± 2.9 $ml.kg^{-1}.min^{-1}$ (Sitkowski, 2002). Similarly within female athletes 800 m values of 63.1 $ml.kg^{-1}.min^{-1}$ (Daniels and Daniels, 1992) were reported versus 53.3 ± 7.0 $ml.kg^{-1}.min^{-1}$ for K1 elite female paddlers (Sitkowski, 2002). The short sprint events (200 m – 500 m), although requiring an above average level of aerobic fitness, above 43 $ml.kg^{-1}.min^{-1}$ (Maud and Foster, 1995), rely on a large contribution from anaerobic energy sources due to the shorter race times, shown in Table 1.1. A direct result of these requirements can be seen in the anatomical build of the athletes, with sprint kayakers exhibiting high scores in mesomorphy (van Someren and Palmer, 2003) and highly developed upper body musculature. It is over these shorter sprint distances (200 – 500 m) that research in this thesis will focus.

1. 2. Equipment

1. 2. 1. Kayak Design

It was shortly after the formation of the ICF in 1946 that the first boat resembling today's modern boats was produced. The kayak was made from fibreglass, which became the most popular material for kayak production over the next 34 years. In 1984 the first plastic kayak was produced (Buchan and Robinson, 2001). This was soon followed by carbon fibre boat development around 1986 for the US Olympic team prior to the 1988 Olympic Games by Van Dusen Racing Boats (Van Dusen Racing Boats, 2005). The construction of racing kayaks has moved on further with the application of new technologies, combining the use of fibreglass, carbon fibre, Nomex honeycomb and epoxy-gel coats to produce the boats used by paddlers today (Van Dusen Racing Boats, 2005).

A brief outline indicating the source of the kayak and its development into the boat that can be seen the world over has been presented, however it is important to understand the basic terms and design components underpinning kayak design. Skilling and Sutcliffe (1966) produced a schematic depicting the shape and terms that will be used to describe factors of boat design within this thesis (see figures 1.1a and 1.1b).

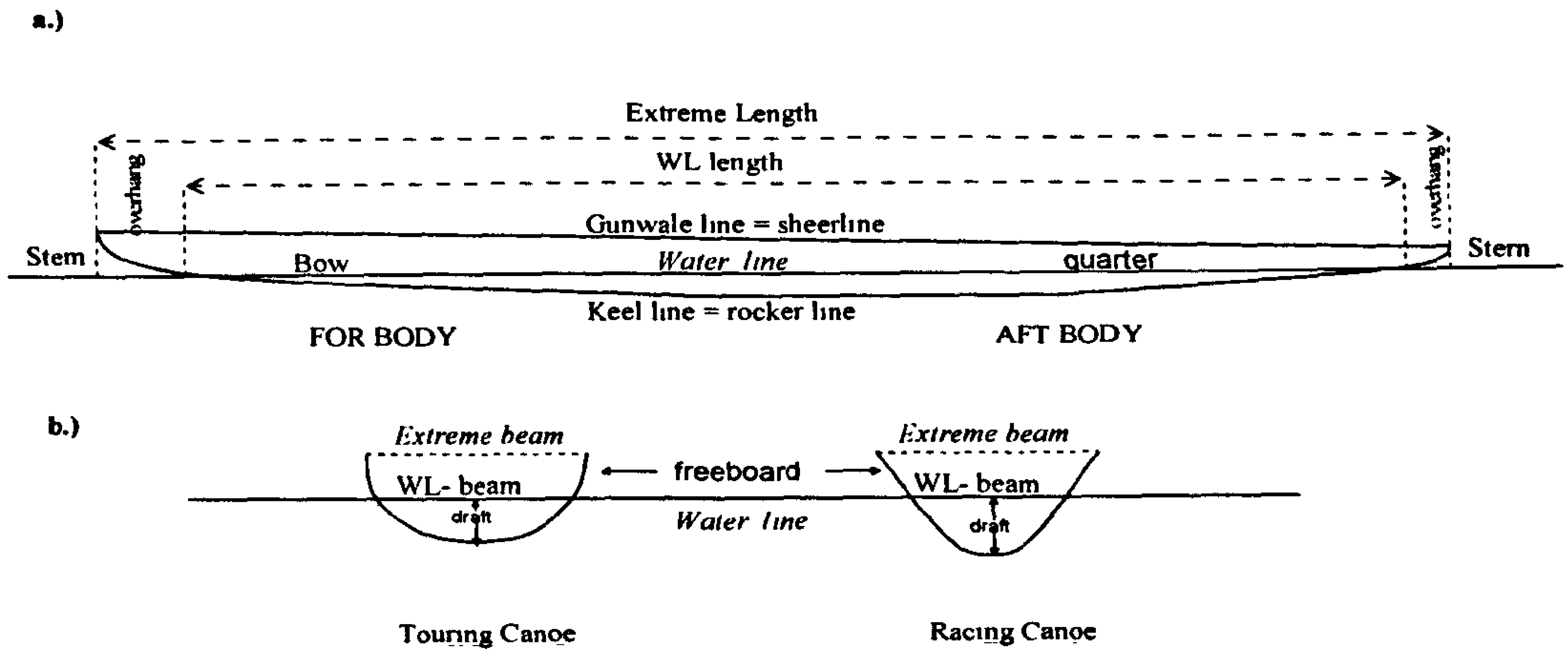


Figure 1. 1a and b. Diagram of boat design and the basic design terms. (adapted from Skilling and Sutcliffe, 1966)

As mentioned previously, the Inuits and other ancient peoples developed different forms of kayak. This was because each boat was designed for specific purposes. This is still an underpinning principle in the design of the kayaks built today, as kayaks used for slalom or white-water racing have different requirements to that of a sprint racing kayak. The boats are therefore designed to incorporate different features to improve certain aspects of performance. The most important factor in sprint racing is speed, therefore the boat needs to be stream-lined to create as little drag as possible. Speed in water based sports is clearly dependent on water resistance, with the majority in kayaking (75 - 90%) coming from frictional resistance or viscous drag between the hull of the boat and the water (Skilling and Sutcliffe, 1966). Skilling and Sutcliffe (1966) identified that the best way to reduce the viscous drag would be to reduce the wetted surface area, suggesting that the best way of achieving this would be to produce a boat with a short deep hull with sections of semi-circular form below the water line. However this hull design would result in the draw of the boat at the stem and stern to be deep (figure 1.1a), which would then serve to increase the wetted surface. To prevent this, the boat would require an increased amount of rocker to ensure that the boat will not draw too deep (Skilling and Sutcliffe, 1966) resulting in very little stability. It is these specifications that are used in sprint kayaks, requiring the paddler to balance the boat throughout the stroke using weight transfer and the paddle to compensate for the natural hull instability.

Skilling and Sutcliffe's (1966) basic principles and theories of improving performance although correct, have been superseded by more recent application of mathematical theories and formulae to improve kayak design and therefore performance. Stejskal (2005) introduces the use of theoretical mathematical formulae, with reference to frictional (drag), wave resistance and total resistance, along with a number of new measures not identified previously by Skilling and Sutcliffe (1966).

Stejskal (2005) indicated that the frictional resistance or viscous drag (FR) between the hull and the water was dependent on several factors:

- Wetted surface area – S (m^2);
- Speed of hull – v ($m.s^{-1}$);
- Viscosity of the water (mu);
- Kinematic viscosity (nu);
- Density of water (rho);
- Coefficient of friction (μ) – CF (assumes smooth hull);
- Length of water line – L (m).

Stejskal (2005) provided a standard hydrodynamic formula as to how these factors influence the frictional resistance (RF):

$$RF=0.5 \times (rho) \times v^2 \times S \times CF$$

Viscous drag occurs between the water and the hull of the boat, more specifically, the boundary layer of the water. The boundary layer refers to the molecules directly in contact with the boat; this boundary layer contributes 99% of the entire viscous drag experienced by the boat. A limitation of the Stejskal (2005) formula was that the hull was assumed to be smooth, however there can be particles which will disrupt the flow of the water over the boats hull (Skilling and Sutcliffe, 1966) which are not visible to the naked eye.

Frictional resistance is not the only factor limiting boat speed in kayaking as wave resistance or residual resistance further increase the forces acting against the boat, reducing the attainable speed. In contrast to frictional resistance, wave resistance is dependent on many more hull parameters and additional factors (Stejskal, 2005). This wave resistance is a very important factor within elite level paddling as it only becomes of concern above the speed of 4 knots (2.06

m.s^{-1}), notably a speed at which elite level sprint paddlers consistently compete (Kendal and Sanders, 1992; Kerwin *et al*., 1992; Hay and Kaya, 1998; Baker *et al*., 1999). The combination of wave resistance and frictional resistance has been termed total resistance. Stejskal (2005) identified these factors and showed a near linear relationship between total resistance and speed above 2.06 m.s^{-1} (figure 1.2).

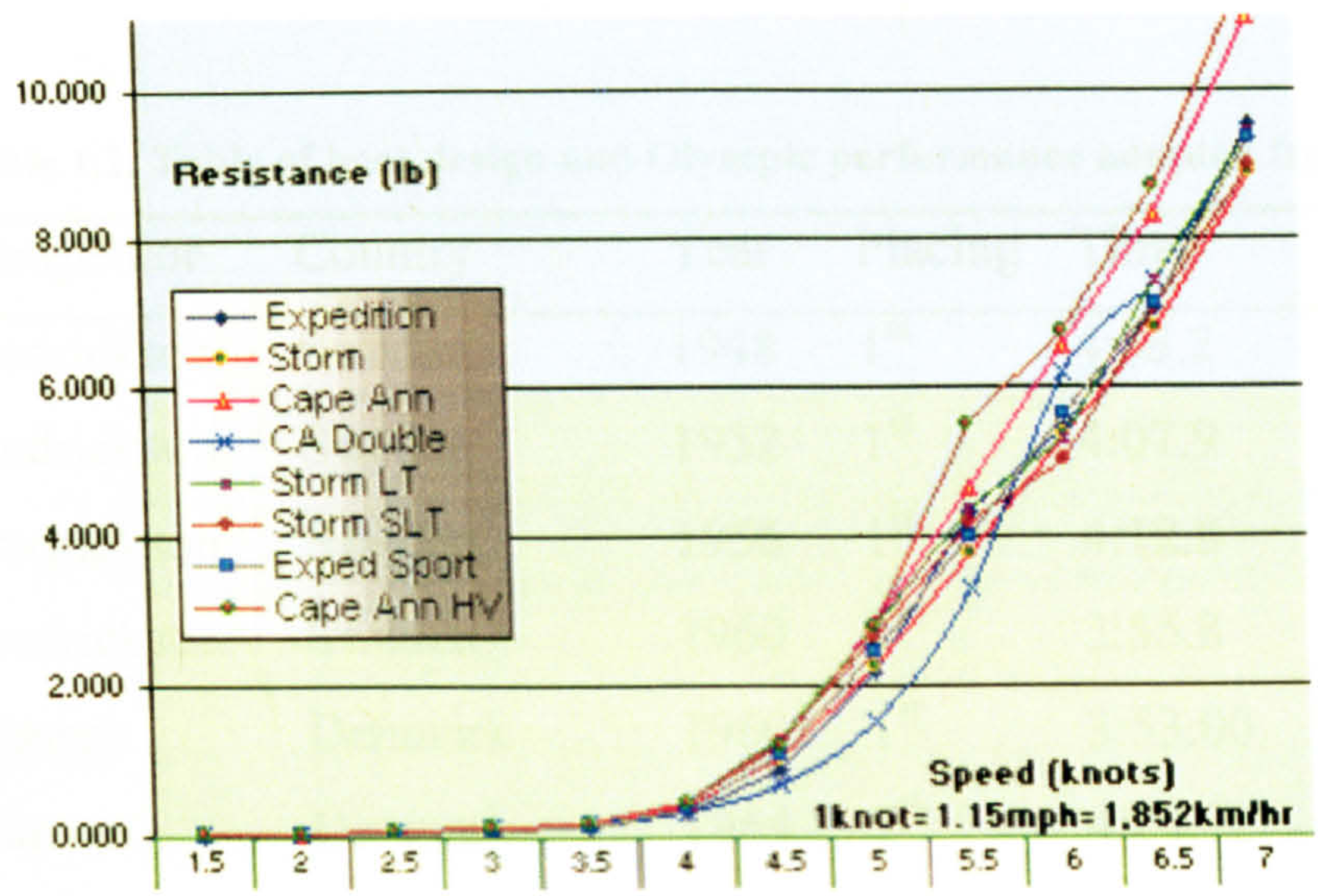


Figure 1.2. Wave Resistance v speed of a number of different kayak designs. (Stejskal, 2005)

The frictional resistance or drag when combined with pressure drag experienced by all objects passing through a liquid provide the form drag experienced by all athletes. In kayaking form drag has two main components, the hull passing through the water and the athlete passing through the air. The hull passing through the water will have the greatest effect on performance (Pendergast, *et al*., 2005) as the water has a greater fluid kinematic viscosity. However due to the standardisation of kayak dimensions by the ICF levels of form drag should remain the same for all competitors, the key factor for paddlers will be to reduce the amount of unwanted boat motion to ensure no increases in from drag due to the pitch and tilt of the kayak.

From the measures identified by Stejskal (2005) it is possible to develop an ideal design for a flat water sprint kayak. As the highest average boat speed is the most important factor, the flat water sprint kayak will need to have the least total resistance with the minimisation of frictional and wave resistance. To achieve this, the boat would require a longitudinal centre of buoyancy (LCB) percentage above 50%, although no upper limit is identified; in addition to this, reducing the amount of sinkage would reduce the wetted surface area, therefore decreasing the frictional resistance. Furthermore, combining this with an elliptical/rounded hull would reduce the midship coefficient (Cm) and area-displacement (AD) ratio, while a high length-beam (LB) ratio would serve further to reduce the total resistance experienced by the kayak. Finally, in the design of the ideal racing kayak, increasing the prismatic coefficient (Cp) would increase hull speed by decreasing the wave resistance, which would be further helped by a reduction of the water-plane area (Awp). Therefore, to produce a kayak that will allow the paddler the opportunity to reach their maximal potential speed, the wetted surface area must be as small as possible to reduce the frictional resistance, whilst the wave resistance must also be minimised to ensure the total resistance is kept at the lowest level possible.

Table 1.2. Table of boat design and Olympic performance adapted from Robinson *et al.* (2002)

Competitor	Country	Year	Placing	Time	Boat Design
Fredrickson	Sweden	1948	1st	4:33.2	Fusiform
Fredrickson	Sweden	1952	1st	4:07.9	V-from kayak
Fredrickson	Sweden	1956	1st	4:12.8	V-form Kayak
Fredrickson	Sweden	1960	3rd	3:55.8	Diamond Shaped
Hansen	Denmark	1960	1st	3:53.00	Diamond Shaped
Hansen	Denmark	1964	7th	4:04.72	Diamond Shaped
Hansen	Denmark	1968	3rd	4:04.39	Diamond Shaped
Hansen	Denmark	1972	7th	3:52.15	Diamond Shaped
Shaparenko	Soviet Union	1972	1st	3:48.06	Delta Shaped
Shaparenko	Soviet Union	1976	5th	3:51.45	Delta Shaped
Sledziewski	Poland	1972	8th	3:53.22	Delta Shaped
Sledziewski	Poland	1976	8th	3:54.29	Delta Shaped
Helm	E. German	1976	1st	3:48.2	Delta Shaped
Helm	E. German	1980	1st	3:48.77	Delta Shaped
Barton	USA	1984	3rd	3:47.38	Delta Shaped
Barton	USA	1988	1st	3:55.27	Eagle
Barton	USA	1992	4th	3:37.93	Eagle
Robinson	Australia	1992	1st	3:37.25	Eagle
Holmann	Norway	1996	1st	3:25.78	Modified Eagle
Robinson	Australia	1996	3rd	3:29.71	Modified Eagle
Holmann	Norway	2000	1st	3:33.26	Modified Eagle (Peaked Deck Design)

These factors have been experimented with since the mid 1900's with boat designs and materials continuously evolving. Robinson *et al.* (2002) identified an apparent correlation between boat design and improved performance (see table 1.2)

Robinson *et al.* (2002) indicate a clear improvement in the race times as boat design altered. Some increases in race times are attributed to racing conditions though the general trend is a clear reduction in race times as design altered. It should be acknowledged however that Robinson *et al.* (2002) do not take into account the professionalisation of sport possible improvements in training and preparatory methods, all of which could have positive influence on performance.

Any alterations in the design of the kayak must conform with the ICF rules on kayak design, which specify that the K1 boat may be no longer than 5.2 m or weight less than 12 kg, whilst K2 boats cannot exceed 6.5 m in length and weigh over 18 kg. No mention of specific materials for the construction are presented, therefore development of new construction materials will continue. Additionally the kayak cannot be concave at any point in its design and the deck may not be higher at any horizontal point than the front edge of the cockpit, with no electronic or moving parts to aid in the performance of the paddler. Furthermore, the kayak may have a single rudder, which may be placed at any point underneath the hull of the boat. Although there are a number of factors that can be utilised to ensure minimal drag, it is essential to ensure that the boat meets ICF regulations if it is to be used in competition.

1. 2. 2. Paddle Design

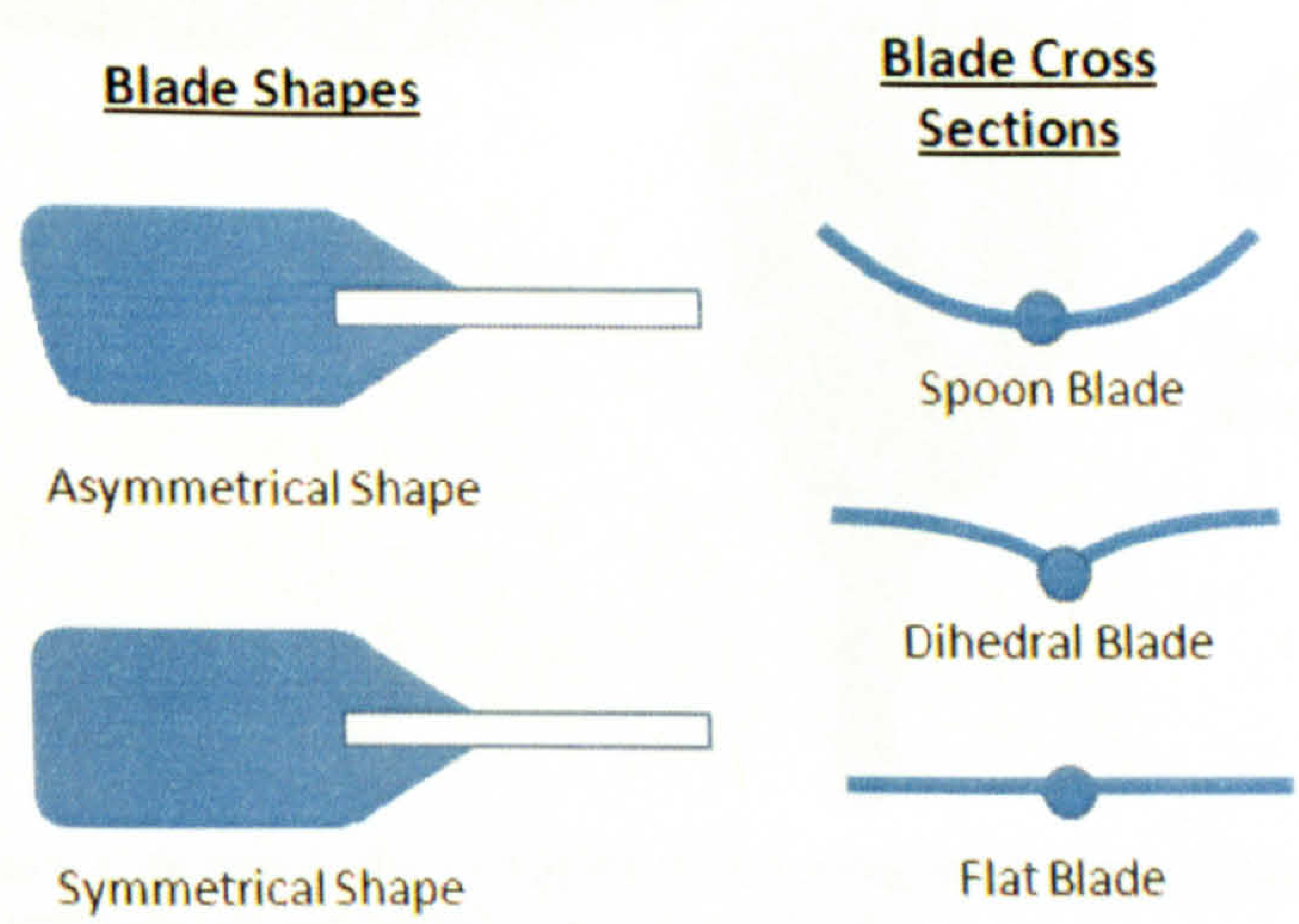


Figure 1.3. Schematics of available paddle blades prior to the evolution of the wing blade (adapted from http://www.pacwave.net/kayak/choosing-a-padle.php 27-04-2004).

Paddle design, as with boat design, is largely determined by its functional use, and on the competitive event i.e. sprint, marathon or white-water. Prior to the mid 1980's there were a number of paddle types; the symmetrical or asymmetrical blade with three cross sectional variations; the flat blade, spoon blade and the dihedral blade (see figure 1.3).

The most popular of these was the flat blade, which was used widely throughout flatwater sprint kayaking (Sanders and Baker, 1998). The flat blade paddle, which relies upon the use of drag forces to propel the boat, is pulled parallel to the direction of travel but in the opposite direction to produce force to propel the kayak forward. This mode of propulsion has a number of problems that will be detrimental to performance, the major drawback being the braking forces produced at the point of blade entry (Sanders and Baker, 1998). Due to propulsion being dependent on the paddle moving backwards parallel to the kayak, the blade needs to be travelling at a higher velocity than the kayak. If the paddle is not, there will be a large braking force at entry and therefore boat speed will be lost. To avoid this occurring the paddle needs to be travelling backwards prior to the point of entry, thus reducing both the braking force and also the pull time (Sanders and Baker, 1998).

In the mid 1980's Swedish scientists overcame these problems using an aerofoil shape resulting in the Swedish wing paddle (figures 1.4a, 1.4b and 1.5). Propulsion with this blade was based on Bernoulli's principle with the blade later evolving into the Norwegian 'wing with a twist' blade.

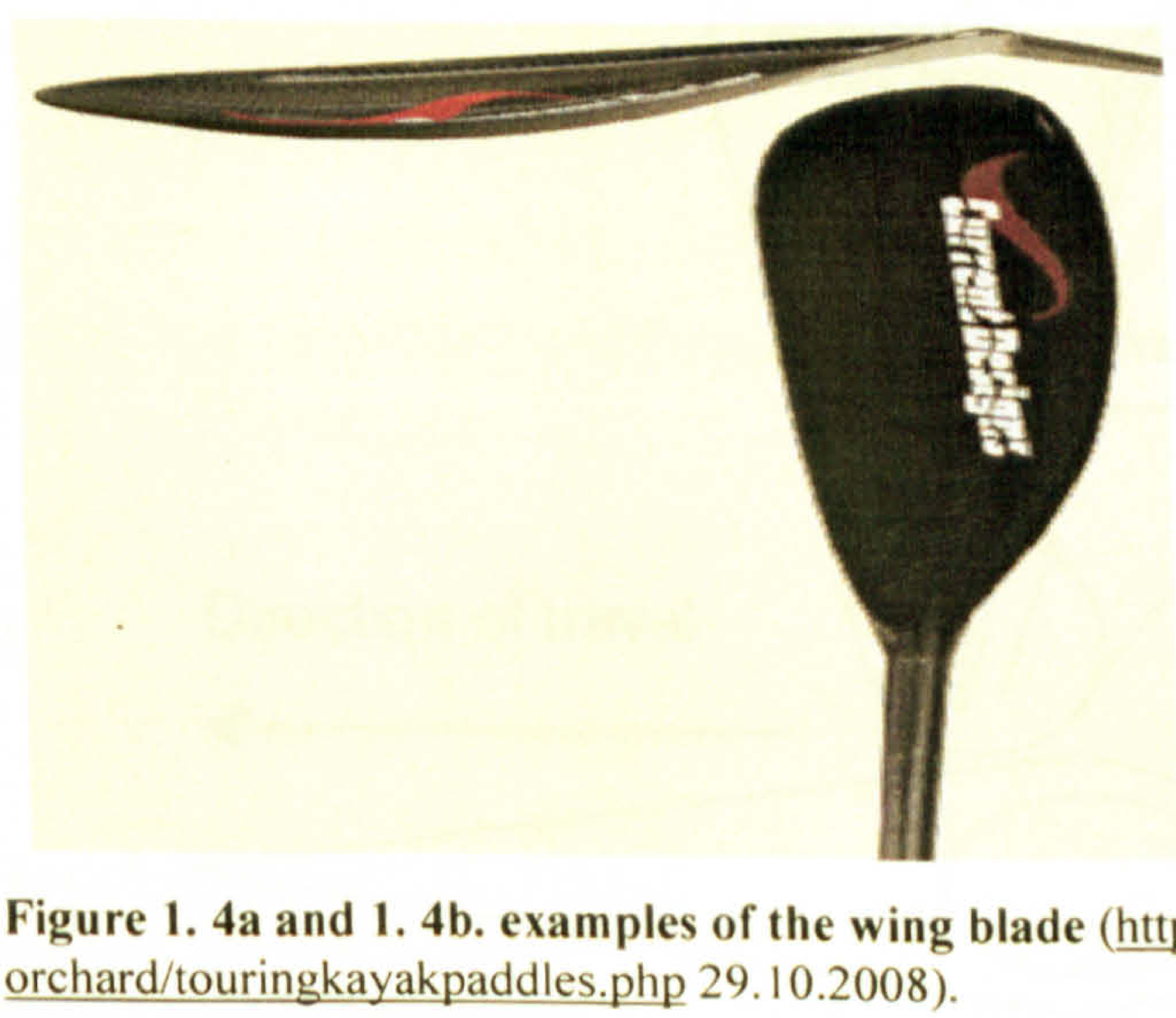


Figure 1. 5. Cross sectional view of the wing blade.

Figure 1. 4a and 1. 4b. examples of the wing blade (http://www.adventuresports.com/product/oak-orchard/touringkayakpaddles.php 29.10.2008).

The wing blade gained its name because the design imitates the shape of an aeroplane wing. It was thought that the use of lift forces would reduce the energy expenditure of the paddling technique as was later indicated by Toussaint *et al.* (1991), Toussaint and Beek (1992) and Jackson (1995). As with an aeroplane wing the molecules travelling across the top of the blade have further to travel over the rounded surface. They therefore have to travel faster than the molecules on the bottom surface of the blade, as it takes the molecules on both sides of the blade the same time to travel from the front edge to the back edge. The molecules travelling faster across the top surface of the blade therefore become wide spread, resulting in a reduction in the molecular density of the water. At the same time the slower moving molecules travelling across the bottom surface stay closer together. Therefore the density of the molecules travelling across the bottom of the blade do not reduce as much as the molecules travelling across the top. This produces a pressure imbalance, with the pressure on the top of the blade becoming lower than that of the water below the blade, creating a lift force in accordance with Bernoulli's principle (Sprigings and Koelher, 1990). As the blade travels through the water it also produces a drag force which comes from the trailing edge of the blade, thus resulting in two forces acting perpendicular to each other, creating a resultant force. It is this resultant force created by the blade of the paddle which results in the paddler and their boat travelling in the direction of the resultant force. Figure 1.6 illustrates the basic principles of the Swedish wing blade, the aerofoil shape at the blade and the rounded leading edge, with its maximum draft at one third of the blade width from the leading edge (Sanders and Baker, 1998).

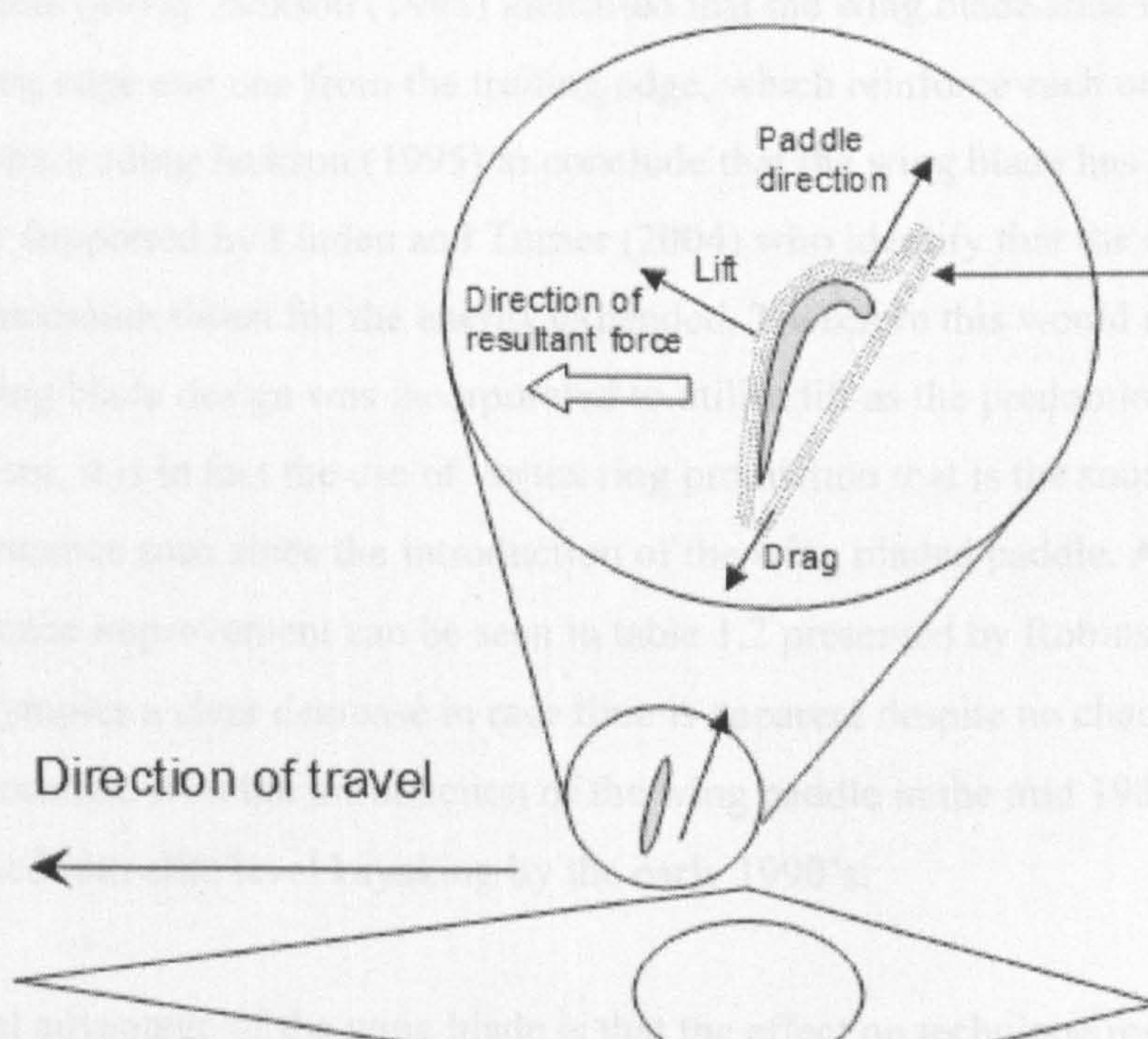


Figure 1. 6. Plane view of the kayak and the motion of the paddle and water molecules around the wing blade.

The wing blade has revolutionised paddling technique as the blade is no longer moved parallel to the kayak but laterally and backward away from the centre line of the boat. This does not completely overcome the braking force problems experienced when using the flat blade paddle.

Unlike the flat blade paddle the wing paddle only creates the braking force if it is not moving laterally as the blade enters the water. If the paddler ensures that the blade is moving as fast as possible when breaking the water surface, the braking force is minimised. As a result of the paddle not needing to be moved backward prior to water entry the paddlers forward reach will be increased. This allows a longer stroke over which the paddler can apply a propulsive force in an attempt to increase boat velocity (Sanders and Baker, 1998).

An additional advantage provided by the wing blade is the increased energy efficiency. Jackson (1995) used mathematical modelling to ascertain the different energy requirements of the wing paddle and the flat blade paddle. Jackson (1995) used values of lift and drag, the time of blade immersion, the total stroke time and the amount of power required from the paddler. However contrasting to the original basis of lift as the primary source of propulsion Jackson (1995) identifies thrust generation through the use of vortex-ring wakes as the propulsive mechanism during paddling. Jackson (1995) used the magnitude of the vortexes shed by the different blades and their motion to identify the efficiency of the paddle. The findings of the study indicated that there was a 15% increase in efficiency from the old style flat bladed paddle (74%) to the wing paddle (89%). Jackson (1995) identified that the wing blade shed two vortexes, one from the leading edge and one from the trailing edge, which reinforce each other creating a larger total vortex leading Jackson (1995) to conclude that the wing blade has greater efficiency. This is further supported by Linden and Turner (2004) who identify that the use of vortex propulsion givens maximum thrust for the energy expended. Therefore this would suggest that although the initial wing blade design was incorporated to utilise lift as the predominant propulsive mechanism, it is in fact the use of vortex ring production that is the source of the improvements in performance seen since the introduction of the wing bladed paddle. An indication of this performance improvement can be seen in table 1.2 presented by Robinson *et al.* (2002). At the 1992 Olympics a clear decrease in race time is apparent despite no change in boat design. This would correlate with the introduction of the wing paddle in the mid 1980's with it being fully introduced into elite level kayaking by the early 1990's.

The final advantage of the wing blade is that the effect on technique results in a cyclical motion, with no distinct beginning and end. The motion results in the large trunk muscles, used to extend the shoulder and rotate the trunk, being utilised more and therefore reducing the amount of work having to be done by the muscles of the shoulder and upper arm.

1. 3. Paddling Technique

The evolution of the wing paddle has not only resulted in increased performance levels, increased efficiency and reduction in race times, but furthermore a dramatic change in the technique required to utilise the paddle optimally. It is important to note at this point that there have been changes in the design and materials used in the construction of kayaks over the past 3 decades, coinciding with the development of the wing blade. These developments within kayak design have reduced the drag characteristics and improved overall performance of the kayak. However the key change within paddling technique is the lateral motion of the paddle during the power/maintenance phase. The lateral motion of the blade is clearly due to the design of the wing blade, as lateral motion of a traditional flat blade would not result in the production of lift forces to propel the kayak forward, regardless of the kayak design. The wing blade exploits this lateral motion through Bernoulli's principle of lift, rather than Newton's third law of motion exhibited in the use of the Greenland flat blade paddle. An additional advantage may have originated from the reduction in the width of the kayak which would allow the blade of the wing paddle to be entered closer to the centre line of the kayak and thus allowing a greater distance over which the paddle could be moved. These changes in paddling technique have been the focus of investigation since the introduction of the wing blade, with many researchers and coaches suggesting the optimum technique to gain benefit from the new blade design.

The wing paddle technique differs greatly from just a basic paddling technique, with many people presenting opinion on the best technique. Imre Kemecsey a former Olympic medallist who became a coach, attempted to pass on his knowledge of technique. The following is an adapted description of technique outlined in Kemecsey's 1986 paper, which starts with blade entry on the left side of the kayak. The technique described here is to be used as a basis for the analysis within research detailed in this thesis.

The technique used by international paddlers was broken down into 4 distinct phases;

1. The catch
2. Maintenance/power phase
3. Recovery
4. Air work

(Kemecsey, 1986)

The paddling cycle described by Kemecsey (1986) starts with paddle entry and the start of the catch (figure 1.7). The catch phase is the shortest of the phases, but is very important, as it is this phase when the paddler accelerates the boat after the apparent reduction in average boat speed during the air work phase. The body is set with the left side of the trunk rotated forward as is the shoulder and hip. The left arm is fully extended forward and low with flexion at the hip and knee. The right side of the body is set with the right arm high above the head, bent at the elbow with the hand positioned wide of the body and the right leg extended. The paddle enters close to the centre line of the boat and is then moved backward and laterally away from the boat.

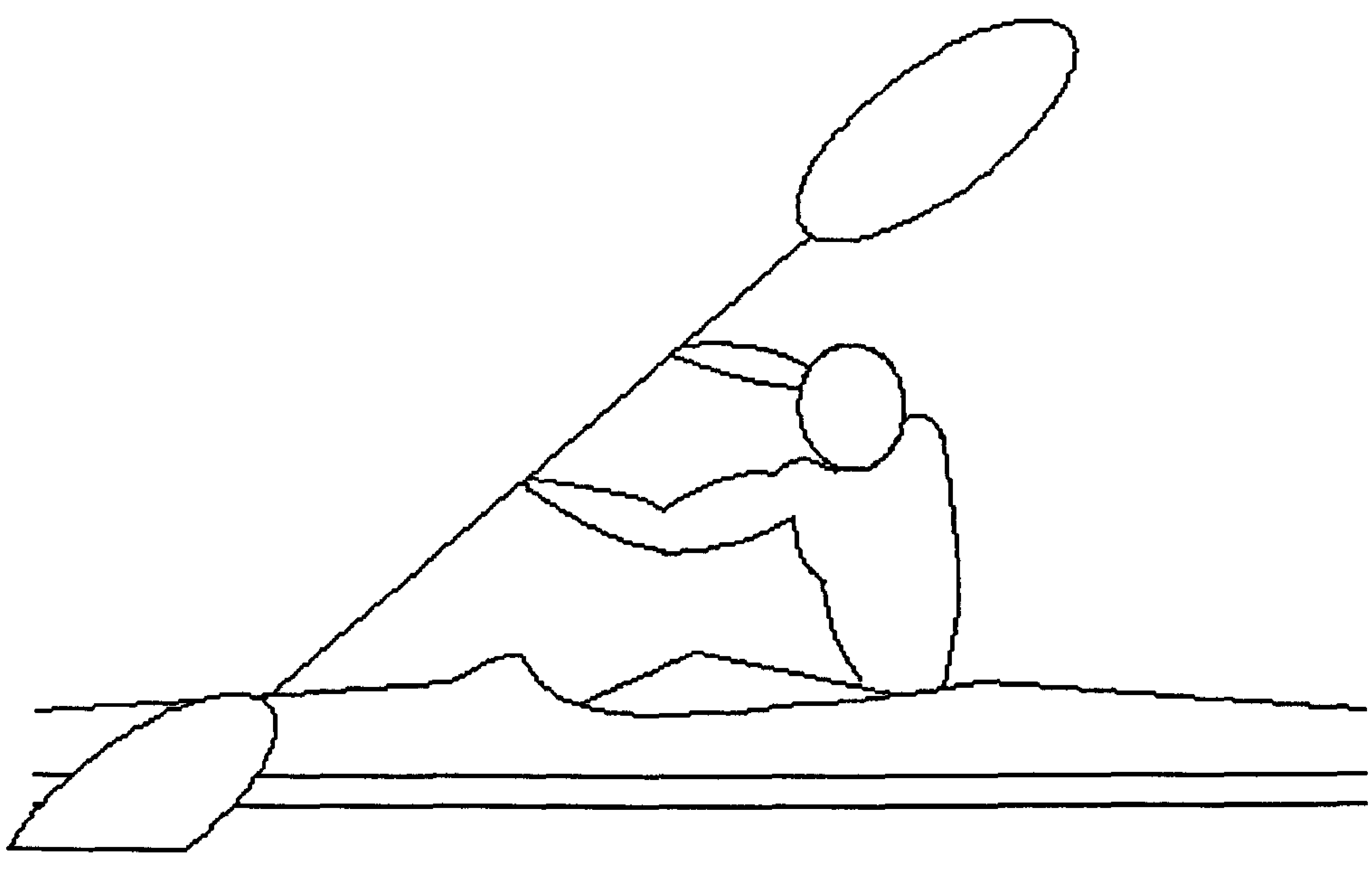


Figure 1. 7. Positioning of the body and wing paddle at the Catch.

In the power/maintenance phase (figure 1.8) the trunk, left shoulder and hip now start to rotate backwards, flexion and abduction occur at the shoulder, the left leg and knee extend and the left hand is moved backward and laterally away from the centre line of the kayak. Initially the left elbow is held in extension, however as the paddle is moved further backward and laterally the elbow flexes. At the same time the right shoulder rotates forward to adduction, causing the extended right arm to adduct until it passes the centre line of the body. At the same time the right hip moves forward and there is an increase in flexion at both the hip and right knee.

The second part of the power/maintenance phase is used to maintain the boat velocity as well as secure an even and smooth run of the boat. The trunk, right shoulder and hip continue to rotate backwards, with abduction of the shoulder and hand. The left leg continues to extend aiding in the rotation of the hips and trunk. The right shoulder continues to flex laterally as the arm comes to the end of its adduction. The right hip comes to the end of its forward rotation and flexion, whilst the knee also ends its period of increasing flexion. At the end of the maintenance phase the blade is moved rapidly backwards to paddle exit. It is at this point as the paddle exits the water at the end of the maintenance phase that the trunk starts to rotate toward the right side.

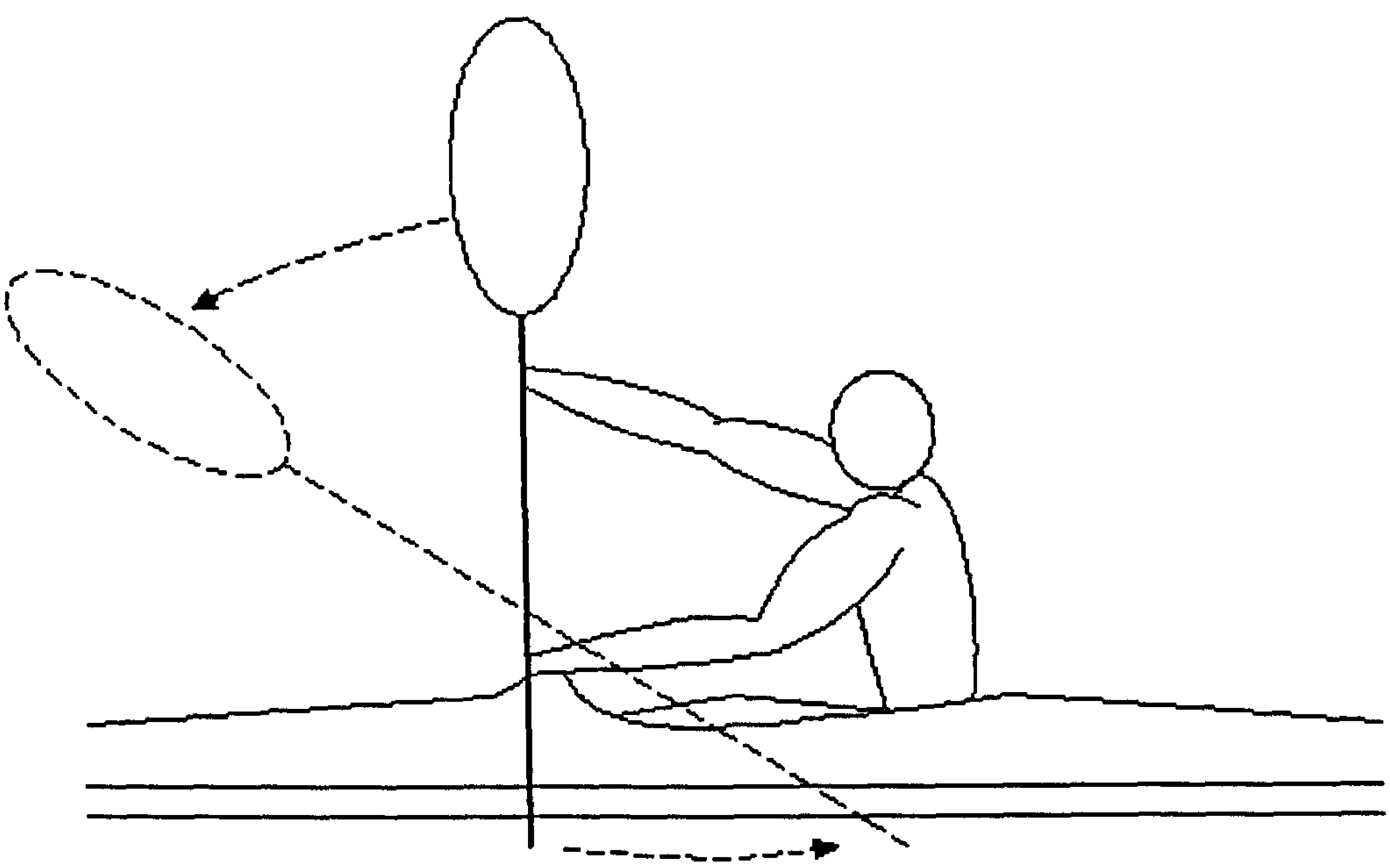


Figure 1. 8. Body and paddle positioning during the power and maintenance phase

The following recovery phase (figure 1.9) is therefore very important as it is at this point that the torso rotates to position the body correctly to make the next catch. However, the rotation of the trunk causes a deceleration of the boat because as the trunk rotates the boat is forced to twist along the longitudinal axis as the paddle is no longer submerged. This rotation of the trunk, starting at the end of the maintenance phase and continuing through the recovery phase, is very important in the reduction of the amount of deceleration during the air work phase (figure 1.10). This rotation of the torso therefore becomes exceptionally fast and is known as a 'popping' recovery. As a result of this rotation of the trunk the right shoulder is already in the correct position ready for the catch. The right knee and hip stay flexed and the right shoulder rotates backwards, causing abduction of the extended right arm. The left elbow then flexes as the left hand moves up and passes by the paddler's head in a high position as the left shoulder rotates forward and causes adduction of the left arm. At the same time the left knee stays extended but the hip flexes as the trunk rotated toward the right side.

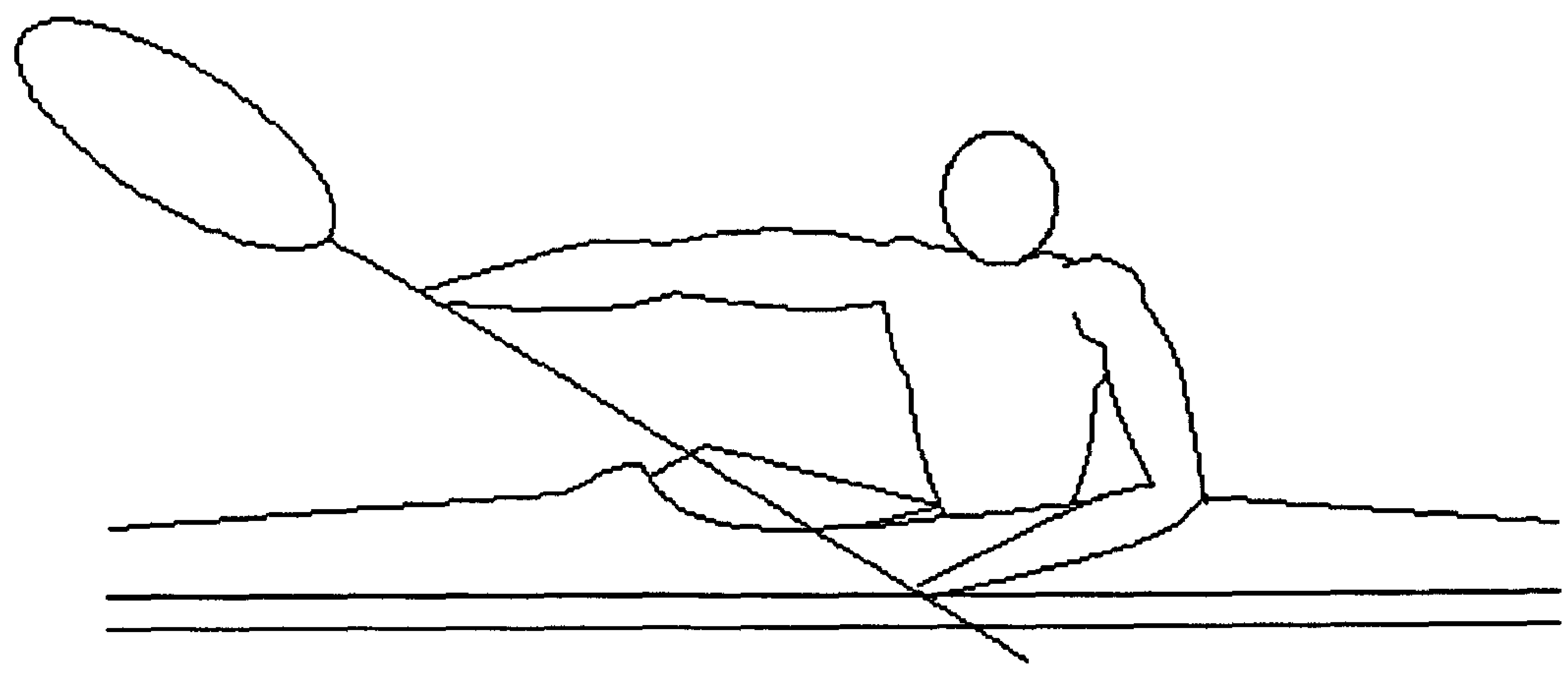


Figure 1. 9. Position of the body and paddle at the start of the recovery

Furthermore, the right shoulder position resulting from the rotation means the shoulder joint and the muscles are pre-set. Consequently a more proficient catch and maintenance phase is possible. This is largely due to the more precise use of the latissimus dorsi to extend the shoulder and rotate the trunk. This increased use of the latissimus dorsi is due to the wing paddle's tendency to 'get stuck', consequently it is important for a paddler to focus on learning the motion sequence prior to the air work to allow the motion of the trunk to become natural. The technique requires a change in the rotation of the trunk and shoulders, with the trunk starting to rotate fractionally before the shoulder rotation, however not too early so as it is apparent to the human eye, instead it would require the paddler to report if they are doing this from their experience or through the use of a high speed camera. All of these motions result in a smooth steady running of the boat.

It is further highlighted that an important factor of an elite level paddler's technique is the ability to put body weight on the paddle between the catch and the end of the pull. This means that the paddler transfers a portion of their body weight onto the paddle to create a continuous downwards pressure, resulting in a greater amount of force being transferred into the paddle, the paddler then lifts their body and boat over the fixed paddle, similar to a pole-vaulter. At this point it is important that the paddler keeps their weight on that side to ensure that there is no loss of energy when transferring the force on to the water. The opposite side of the body then mirrors this pattern of movement as the right paddle stroke is completed.

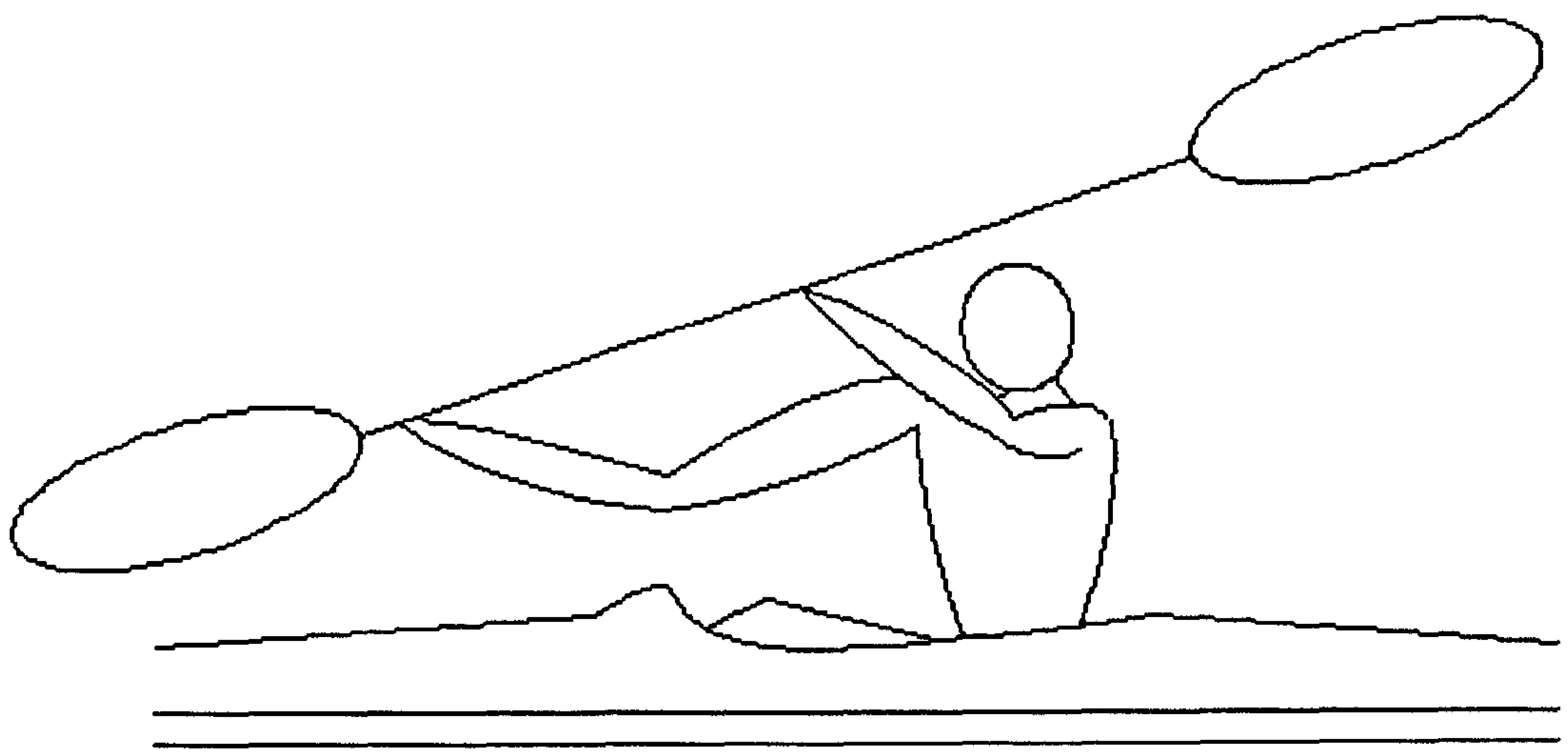


Figure 1. 10. The positioning of the body and paddle during the air work

1. 4. Overview of previous literature

Previous literature has identified that flatwater sprint kayaking involves the simultaneous activity of balancing both the boat and the body whilst applying the maximal pressure to the paddle at the most efficient rate (Kemecsey and Lauder, 1998) to ensure maximal power transition from the performer and paddle to the water. The success of a performer is therefore highly dependent on the technique used, which can be the determining factor between levels of ability. Previous research has focused greatly on quantitative data as a tool to investigate kayaking technique (Yoshio *et al.*, 1974; Plagenhoef, 1979; Mann and Kearney, 1980; Kerwin *et al.*, 1992; Sanders and Kendal, 1992a; Baker *et al.*, 1999), whilst others have focused upon performance prediction (Jackson, 1995; van Someren and Palmer, 2003), paddle design (Kendal and Sanders, 1992; Kerwin *et al.*, 1992; Sanders and Kendal, 1992b; Sanders and Baker, 1998), on-water force analysis (Zsidegh, 1981; Aitken and Neal, 1992; Mononen and Viitasalo, 1995; Mononen *et al.*, 1994), injury occurrence (Lovell and Lauder, 2001; Schoen and Stano, 2002), physiological demand and characteristics (Sidney and Shephard, 1973; Zsidegh, 1981; Tesch *et al.*, 1983), the effects of strength training on performance (Issourin, 1989), equipment configuration (Ong *et al.*, 2005 and 2006) and the development and evaluation of dry land ergometry for training and assessment (Campagna *et al.*, 1982 and 1987; Petrone *et al.*, 2006; Fleming *et al.*, 2007).

The research presented here is a brief overview of the current literature investigating kayaking technique and performance. Further in depth analysis of the relevant papers will be included at the outset of the subsequent chapters as the current thesis develops.

1.4.1. Flat Blade Research Literature

Early research (Ariel, 1977; Campagna *et al.*, 1982; Mann and Kearney, 1980; Plagenhoef, 1979) used two dimensional kinematic analysis as the predominant tool of investigation. Ariel (1977) used high speed (100 Hz) analysis identifying key performance factors within the US Olympic kayak squad, including the importance of a reduced forward reach, and important relationships between the trunk and the paddle/arm acceleration during the stroke. Furthermore Ariel (1977) identified that the reduced forward reach was important in an efficient transfer of force, however Ariel (1977) had no basis for the claim as no measure of force production was included within the investigation. Similarly to Ariel (1977), Plagenhoef (1979) analysed the performances of elite level paddlers during competition and practice sessions from which it was identified that only during close races did the paddlers perform to their maximum levels and therefore footage from practice sessions was not representative of peak performance. In addition to this Plagenhoef (1979) indicated that stroke rate was not key to performance, prescribing a smooth rhythmical stroke for greater performance. Furthermore Plagenhoef (1979) compartmentalised the stroke into 4 distinct phases, identifying the ideal proportion each should contribute during the stroke (table 1.3).

Table 1.3. Plagenhoef's (1979) division of the kayak stroke, including ideal and found percentages.

Phase Number	Phase Description	Stroke Time Percentages	
		Ideal	Findings
1	Paddle entry to the point where the paddle is in the vertical plane	22	20-25
2	Paddle in the vertical plane to the end of top arm forward motion	42	26-46
3	End of top arm forward motion to paddle exit	5	0-20
4	Paddle exit to paddle entry	31	25-35

Mann and Kearney (1980) implemented the same stroke phases introduced by Plagenhoef (1979) investigating the techniques of 11 (9 male; 2 female) paddlers to determine the key biomechanical and performance variables. From the findings Mann and Kearney (1980) proposed the importance of a vertical paddle position during the power maintenance phase and that draw and trust sections, defined as the legs and arms, should work in conjunction with each other to optimise technique and include large muscles of the body in the production of propulsive forces. Although the early research (Ariel, 1977; Mann and Kearney, 1980; and

Plagenhoef, 1979) provided important performance parameters for alteration and improvement the introduction of the wing blade by Scandinavian scientists made the findings obsolete due to the evolution due to the change in the propulsive mechanisms from drag forces to lift and vortex propulsion.

1.4.2. Wing Blade Literature

Similarly to early research kinematic analysis continued to dominate as the principle investigative tool employed during the analysis of technique changes resulting from the introduction of the Scandinavian wing blade paddles (Kendal and Sanders, 1992; Kerwin *et al.*, 1992; Sanders and Kendal, 1992a; Sanders and Kendal, 1993; Hay and Kaya, 1998; Baker *et al.*, 1999; Ong *et al.*, 2006). Kerwin *et al.* (1992), in an attempt to develop an on water three dimensional analysis system, investigated the differences in stroke technique between the traditional and wing bladed paddle. Kerwin *et al.* (1992) identified that the techniques were significantly different in patterns of motion, with the findings indicating that use of the wing blade produced a higher stroke rate (wing: 57 strokes.min; traditional: 47 strokes.min). This lead Kerwin *et al.* (1992) to propose stroke rate to be a key performance factor using the higher average velocity (wing: 4.79 $m.s^{-1}$; traditional: 4.18 $m.s^{-1}$) produced when using the wing bladed paddle to support this proposition. Both Sanders and Kendal (1992a) and Hay and Kaya (1998) corroborate this finding each expressing the importance of stroke rate as the key determinant of average kayak velocity. Hay and Kaya (1998) establish that stroke rate was the key determinant of average velocity for female paddlers, however male paddlers displayed significant relationships between stroke rate and velocity ($r = 0.8$) and stroke length and velocity ($r = 0.55$). This indicated that although rate was of primary importance stroke length was also required to maintain higher average velocities.

From this work Sanders and Baker (1998) summarised that the wing blade paddle provides 6 advantages over the traditional flat blade paddle, including:

1. Allows the paddler to find 'still water';
2. Improves efficiency of transferring energy to the water;
3. Promotes a rhythmic fluid paddling technique;
4. Reduces the braking forces at paddle entry;
5. Increases the amount of time the paddle stays in the vertical position;
6. Enable the body's muscle, joint and lever system to be used more effectively.

(Adapted from Sanders and Baker, 1998)

Other researchers moved away from on-water analysis focusing more on training techniques and the validity of different ergometers in reproducing correct technique (Campagna *et al*., 1982 and 1987; Petrone *et al*. 2006; Fleming *et al*., 2007). Campagna *et al*., (1987) maintained the dominance of kinematic investigation using high speed footage (Hz) to compare the motion patterns of technique on-water and on-ergometer. Campagna *et al*. (1987) summarised that the techniques were no significantly different, however no measure of how similar the techniques were was provided. Fleming *et al*. (2007), as Campagna *et al*. (1987), compared on-water to on-ergometer technique, however Fleming *et al*. (2007) used electromyography to ascertain muscle firing patterns during technique in a unilateral study of the body. Findings did not corroborate those of Campagna *et al*. (1987) as a significant difference in the pattern of activation of the anterior deltoid was exhibited when paddling on-ergometer, characterised by an increase in activity level and variation in timing.

In addition to the evolution of technique it has been shown that the introduction of the wing blade altered the manner in which propulsion was developed. This directed researchers to the importance of force production during paddling with Robinson *et al*. (2002) stating that:

> " ... in no other comparable on-water sport is the relationship between absolute force development and the manner of its production more critical to the final outcome than sprint canoeing and kayaking"
>
> Robinson *et al*. (2002) pp.68.

This can be seen in the research investigating force production and its relationship with average velocity (Stothart *et al*., 1987; Aitken and Neal, 1992; Mononen *et al*., 1994; Mononen and Viitasalo, 1995; Logan *et al*., 1997) and resultant investigation into strength training and force production (Issourin, 1989; Liow and Hopkins, 2003). Aitken and Neal, (1992) and Stothart *et al*. (1987) focused on the development of systems that could be implemented during on water paddling to measure the forces produced by the paddler. Both systems were based on the measurement of the deformation strain gauges positioned along the shaft of the paddle with both sets of researchers concluding that the equipment and protocol were accurate and reliable enough to be employed as part of training and monitoring regimes. Mononen and Viitasalo (1995) utilising a similar protocol to those presented by Aitken and Neal (1992) and Stothart *et al*. (1987), tested the proposition of Robinson *et al*. (2002) attempting to establish the relationship between force production and average velocity. Results identified that significant strong positive relationships existed between mean force and average velocity ($r = 0.79$) and peak force and average velocity ($r = 0.7$). Therefore providing empirical evidence for the link between force production and velocity thought to exist by a number of scientists (Stothart *et al.*, 1987; Aitken and Neal, 1992; Mononen *et al.*, 1994; Mononen and Viitasalo, 1995; Logan *et al.*, 1997; Robinson *et al.*, 2003).

Findings from the past research provide clear evidence for the improvements the wing blade design have created and the important upper body technique factors that are required to enhance average velocity, the key performance variable. Furthermore the identification of the importance of force production has provided paddlers and coaches alike with further information and key performance factors that require development. However, previous studies investigating kayak technique and performance have not been without limitation, with many of the researchers displaying clear understanding of the methodological limitations and the validity and accuracy of the findings, highlighting future improvements and areas of interest that would require further investigation to be conducted. However as a result further research is required to affirm these findings and to enhance the understanding of the kayak stroke with greater focus to be applied to the body as a whole as current knowledge is entirely anecdotal.

1.5. Thesis Research Rationale

Flatwater sprint kayaking is a complex activity requiring the simultaneous activities of balancing the boat and the body whilst exerting the maximal force at stroke rates upward of 60 strokes per minute. Many researchers have investigated the finer points of the paddle and arm motion in an attempt to identify the importance of stroke rates, stroke lengths and patterns of motion to performance (Sanders and Kendal, 1992a; Hay and Kaya, 1998). Vitally there has been no investigation into the contribution of the body as a whole; instead many researchers treat the majority of the body as a redundant base around which the arms and paddle are moved. A small number of researchers (Shepherd 1987; Logan and Holt, 1997) and additional coaching texts have highlighted that this is not accurate, indicating the trunk and legs are instrumental within a successful technique (Kemecsey, 1986) but with no empirical evidence.

It is this area that will be addressed within the current research thesis, through the use of kinematic, electromyographical, electrogoniometric and kinetic analysis of the entire body. The primary focus of the research thesis will therefore be to improve the understanding of the relationship between the contribution of the trunk and lower body movement to performance in flatwater sprint kayaking. To attain a greater understanding a comprehensive qualitative analysis of the flatwater sprint kayak stroke will be conducted, with specific focus on the motion and contribution of the trunk and lower limbs to kayaking technique and performance.

1.6. Thesis Aims

The current thesis has a single primary aim which is to:-

- To improve the understanding of the flatwater sprint kayaking stroke, through biomechanical analysis of upper body, trunk and lower body movements and their importance to performance.

Within the primary aim two major sub aims are to:

- Conduct a detailed quantitative and qualitative analysis of competitive flatwater kayaking.
- Identify the motion and contribution of the trunk and lower limbs to kayaking technique and performance, more specifically the effect on boat speed and force production.

2. Notational Analysis of Flatwater Sprint Kayaking

2.1. Introduction

Sprint kayaking technique is a series of complex motions involving the simultaneous activity of balancing the boat, whilst ensuring an efficient maximal force transition is attained through the paddle to the water (Kemecsey and Lauder, 1998). The success of a performer is therefore highly dependent on the technique used, which possibly may be utilised as a means of determining skill level. Previous research into sprint kayaking has revolved around the evolution of technique due to the introduction of the wing paddle during the mid 1980's (Sanders and Baker, 1998). The principle of the wing blade paddle's design relied upon the use of lift forces to propel the paddler and kayak utilising Bernoulli's Principle, in the same way an aeroplane wing causes an area of low pressure on the rounded surface to enable the plane to take off. The wing blade has a clear aerofoil shape with the maximum draft one third from the leading edge (figures 1.4a, 1.4b and 1.5). More recently theory of the propulsive mechanism has changed with focus turning to the vortex shedding properties of the blade, with Jackson (1995) indicating an increase of 15 % in efficiency when using the wing blade through the study of the vortices produced when compared to the traditional flat blade.

Much investigation has focused on the techniques and performances of elite level competitors (Ariel, 1977; Plagenhoef, 1979; Kerwin *et al.*, 1992; Sanders and Baker, 1998), however little previous research has compared elite and amateur paddlers in terms of technique. One of the papers was Sanders and Kendal (1992a) who investigated the differences in technique between elite and novice paddlers using the wing paddle. Five subjects were analysed using two phase locked cameras, set at 100 fps with markers positioned at the joint centres of the wrist, elbow, humeral axis, xiphoid process, 7th cervical vertebrae and the vertex of the head. In addition to these anatomical landmarks, the motion of the paddle, stroke length, pull time, glide time, stroke frequency and average boat velocity were measured. The subjects paddled at maximum velocity toward a stationary camera at the end of the lake, therefore the front on footage varied between 20 - 40m from the camera. The variables to be measured were selected in accordance with a performance model developed by Sanders and Kendal (1992a) of the most important contributors to performance. Within the model the key outcome variable was average velocity, under which two key contributors, as corroborated later by Hay and Kaya (1998), were identified as stroke length and stroke frequency (or rate). Within each of these further sub-contributors were identified and analysed including pull and glide duration and length, slip, paddle path, trunk rotation, arm extension and hand position.

Sanders and Kendal's (1992a) model provides a basic template of the factors that are incorporated within the kayaking technique 'cycle', thus contributing toward performance. Sanders and Kendal (1992a) identified that the most important factor in determining average boat velocity and ability level was the stroke frequency (or stroke rate) ($P < 0.05$). Findings further supported this with the glide ($P < 0.05$) and pull ($P = 0.06$) times providing a way of determining between ability levels, with the elite paddlers exhibiting a much shorter glide and pull time than the novice paddlers. These significant findings highlight how the elite paddlers produced a faster stroke rate. By reducing the pull and glide phases of the stroke a greater number of strokes can be completed. This was also identified by Kerwin *et al.* (1992) who showed that an increased paddle rate resulted in increased average boat velocity. However, Hay and Kaya (1998) disagreed that shortening the pull phase was important, conversely they indicated that an increased stroke rate in conjunction with a increased stroke length would produce the fastest average boat speed.

Sanders and Kendal (1992a) identified that paddle entry could distinguish between elite and novice paddlers. Elite paddlers were shown to enter the water closer to the longitudinal axis of the kayak and move the blade laterally throughout the whole of the pull phase, whereas the lesser skilled paddlers started the pull further away from the kayaks longitudinal axis and started to move the paddle back towards the kayak at the end of the stroke (Sanders and Kendal, 1992a). Although the findings provide interesting factors for consideration, the small subject numbers limit the application of these results to general paddling populations.

Hay and Kaya (1998), similarly to Sanders and Kendal (1992a), investigated technique utilising average speed as the key measure of performance, attempting to determine the importance of stroke rate and length during paddling. Hay and Kaya (1998) collected data from the 1997 US national championships and the World championships, analysing the techniques of 331 subjects both male (n = 188) and female (n = 143), and senior and junior, over 200 m, 500 m and 1000 m. The footage was collected at 60 Hz from a camera positioned perpendicular to the plane of motion covering lanes one to five, with a 12.5 m field of view in lane one and 25 m in lane five.

Hay and Kaya (1998) selected each subject's fastest performance as a selection method, however if the clarity of the footage from that performance was not good enough then that subject was completely removed from the study. Technique was analysed through complete stroke cycles with the start of the paddle cycle being determined as the point the blade farthest from the camera crossed the line of the foredeck. The length of the kayak (5.4m) was used to calibrate the footage, from which the stroke rate, stroke length and boat speed were determined. The test re-test repeatability of the digitisation technique was determined through the use of correlations, results indicated very good repeatability ($r = 0.94 - 0.99$). The significance level was set at $\alpha = 0.001$, this was chosen because of a high incidence of Type I errors when large numbers of t-tests are performed. However Hay and Kaya (1998) further provided significances to the $\alpha = 0.01$ and $\alpha = 0.05$ as these were seen to be the universal standards set for significance by most authors.

Hay and Kaya's (1998) findings exhibited significant strong positive correlations ($P < 0.001$) between stroke rate and boat speed for males and females over all three events, however only three significant strong positive correlations ($P < 0.001$) were found between the stroke lengths and boat speed. For male paddlers a correlation of $r = 0.72$ was apparent between stroke rate and boat speed during the 1000 m event, further correlations of $r = 0.77$ for the 500 m and $r = 0.8$ for the 200 m were also identified. The female paddlers exhibited a similar pattern as the strength of the correlations between stroke rate and boat speed increasing as the race distance shortened (1000 m, $r = 0.7$; 500 m, $r = 0.78$; 200 m, $r = 0.78$). Male paddlers also exhibited modest correlations between the stroke length and boat speed, these were still stronger than females, with the 1000 m ($r = 0.53$) and 500 m ($r = 0.55$) races at the $P < 0.001$ significance level, while the 200 m ($r = 0.36$) was significant to $P < 0.01$. The female paddlers exhibited very poor correlations for the 200 m ($r = 0.2$) and 1000 m ($r = 0.37$) significant to $P < 0.05$, while the correlation was significant to the $P < 0.001$ level for the 500 m ($r = 0.46$) event.

Table 2.1. Results from Hay and Kaya (1998)

Distance (m)	Male			Female		
	Boat Speed $m.s^{-1}$	Stroke Rate $strokes.s^{-1}$	Stroke Length m	Boat Speed $m.s^{-1}$	Stroke Rate $strokes.s^{-1}$	Stroke Length m
200	5.41 ± 0.52	1.13 ± 0.11	4.81 ± 0.3	4.56 ± 0.46	0.99 ± 0.1	4.61 ± 0.29
500	4.5 ± 0.51	0.89 ± 0.09	5.09 ± 0.37	3.81 ± 0.45	0.81 ± 0.09	4.7 ± 0.36
1000	4.18 ± 0.41	0.79 ± 0.07	5.29 ± 0.37	3.95 ± 0.31	0.79 ± 0.06	5.03 ± 0.32

From their findings Hay and Kaya (1998) proposed that the male paddlers used both the large stroke lengths and high stroke rates to produce the best performance, female paddlers however relied solely on increasing stroke rate to improve boat speed. Furthermore Hay and Kaya (1998) found that as the race distance decreased stroke rate and boat speed both increased, whilst the stroke length decreases (see table 2.1). When comparing gender, Hay and Kaya (1998) found that males exhibited higher stroke rates in both the 200 m and 500 m events, and higher stroke lengths and boat speeds in all events than their female counterparts. The stroke rates during the 1000 m event was the only instance in which males and females exhibited similarities (males = 0.79 ± 0.07 strokes.s^{-1}, females = 0.79 ± 0.06 strokes.s^{-1}).

The aim of Hay and Kaya's (1998) study was to determine whether stroke rate or stroke length was the most important contributor to boat speed as much previous research contested this key factor (Kerwin *et al.*, 1992; Sanders and Kendal, 1992a; Sanders and Baker 1998). The findings indicated that the stroke rate was the dominant influence in the determination of boat speed, reinforcing the findings of Sanders and Kendal (1992a) and Kerwin *et al.* (1992), although further research may be required to identify additional factors that may have been over looked previously. However Hay and Kaya (1998) failed to elaborate on the underpinning factors within technique that contribute to stroke rate and length.

Baker *et al.* (1999) also utilised kinematic data as an investigative tool for application within the coaching of kayaking technique. More specifically the research aimed to determine differences between male and female paddlers that would affect the way the different genders should be coached. Ten national level paddlers (6 male, 4 female) completed 3 trials consisting of a 200 m acceleration phase, prior to the calibrated area which was 6 m long and 2 m high and 2 m wide, though no indication what type of calibration object nor its accuracy were provided. The subjects were asked to paddle at the equivalent speed of the national championship winners in the 1000 m for the men and the 500 m for the women (speeds not reported). Footage was collected using two gen-locked S-VHS video cameras operating at 50 Hz, with the shutter speed set at 1/1000 of a second. The middle knuckles, wrists, elbows and shoulders on both left and right sides were digitised, with the addition of two markers on the shaft, two at the neck between the hand and the blade of the paddle and two further markers, one on the bow of the kayak and the other on the stern. The direct linear transformation (DLT) (Abdel-Aziz and Karara, 1971) method was used to produce a three dimensional reconstruction of the points, over which a quintic spline was used to smooth the data, using ten frames pre and post the cycle of interest to minimise end effects.

Analysis was undertaken using the opinion of two coaches and findings in previous literature from which analysis was separated into right and left sides. Measures analysed included total and intra-stroke velocities, timing and displacement measures, two and three dimensional measures of the entry and exit angles, and trunk rotation (represented by shoulder rotation). Findings indicated that there was a significant difference between males (4.94 ± 0.17 m.s^{-1}) and females (4.50 ± 0.33 m.s^{-1}) in velocity ($P = 0.01$) and intra-stroke velocity, therefore a significant difference in distance covered during stroke (male = 2.66 ± 0.19 m, females = 2.47 ± 0.16 m; $P = 0.03$) and glide (male = 1.04 ± 0.06 m, female = 0.93 ± 0.09 m; $P = 0.01$) was reported. There was however no significant difference identified in the spatial analysis, therefore suggesting that techniques between genders were similar and that adoption of different training technique for males and females was unnecessary. Baker *et al.* (1999) stressed that their findings were only part of a preliminary study as the group sizes were small (6 males and 4 females) and so may have influenced the statistical analyses, which were not described. An important consideration to rise from Baker *et al.* (1999) is the measurement of trunk rotation, despite the inaccuracy of the methods of measurement. The acknowledgement of its possible importance, leading from the early indications provided by Sanders and Kendal (1992a), displays that this may have an important role in velocity production. However little attention is paid to the trunk rotation measure in the results and discussion and so it is still to be established how influential this motion is within technique.

A more recent study by Petrone *et al.* (2006) investigated the rotary motion of the trunk during on-ergometer paddling using kinematic and kinetic analysis. Subjects consisted of female elite level paddlers (n = 5), from which Petrone *et al.* (2006) measured the patterns of motion in the upper body, flexion of the knees and the force imparted onto the footplate using a specifically assembled dynamometric footpad (Petrone *et al.*, 2006). Subjects were prepared with markers on all major upper body joints with further markers on the head, paddle, 7th cervical and 12th thoracic vertebrae, and the left and right Posterior Superior Iliac Spine. Furthermore rotational potentiometers were attached to the knees to measure changes in knee angle during paddling and video footage was collected using 6 infrared coaxial 50 Hz cameras. Subjects then completed 4 trials under different conditions:

1. Fixed seat at 70 strokes per minute;
2. Fixed Seat at 90 strokes per minute;
3. Rotating seat at 70 strokes per minute;
4. and, Rotating seat at 90 stroke per minute.

From each trial 50 stroke cycles were collected, ten of which were selected for further analysis. Kinematic data was digitised to provide trajectories and angles of the paddle and appropriate segments. However, results presented by the authors are limited, providing values for just 2 subjects (S1 - Olympic K1 500m Gold Medallist and S5 - K2 National 5000m champion) for comparison in paddle motion. All paddlers trunk rotation values were presented, with only S1's knee flexion and force values available to the reader.

Paddle trajectory results reported asymmetry between sides in all paddlers, with the comparison between S1 and S5 indicating a wider stroke for S1 and longer paddle path. Force characteristics and knee motion presented for S1, exhibited greater knee flexion in the right knee for all conditions, with the rotating seat (70 spm and 90 spm – Left 63°, Right 65°) causing greater flexion than the fixed seat condition (70 spm – Left 65°, Right 71° and 90 spm – Left 66°, right 72°). Little difference was found between right and left force production with no pattern of either right or left imparting greater force. The rotating seat exhibiting clearly higher force values than the fixed at both 70 spm (Fixed, L - 253 N, R - 264 N, Rotating, L - 362 N, R - 355 N) and 90 spm (fixed, L - 319 N, R - 320 N, Rotating, L - 465 N, R - 46 N). Trunk rotation highlighted that subjects 1 and 4 exhibited the greatest symmetry, with all other paddlers showing asymmetrical results.

Petrone *et al.* (2006) concluded that despite variation in ability all paddlers exhibited factors that required improvement and that kinetic and kinematic parameters correlated with skill level, however no indication of the statistical evaluation conducted were reported. Furthermore Petrone *et al.*'s (2006) conclusions were limited by poor reporting of findings which undermined the claims presented. Furthermore the use of an ergometer could influence paddling technique (Fleming *et al.* 2007) when compared to on water paddling. Despite these limitations Petrone *et al.*'s (2006) inclusion of leg flexion and trunk rotation displayed further recognition from scientists that the trunk and legs may be important.

The inclusion of the trunk and legs in the consideration of technique by the scientific community (Sanders and Kendall, 1992a; Baker *et al.*, 1999; Petrone *et al.*, 2006; Fleming *et al.*, 2007) exhibits progressive understanding that the motion of the arms and paddle may not be the key to understanding velocity production during kayak paddling. This may have stemmed from coaching texts such as those of Kemecsey (1986) in which the full body is considered during technique. However despite recognition, scientific research has not established the importance of the entire body and its individual segments in performance or how these may be used as technique and skill level determinants.

2.2. Aim

The aim of this research was to determine any variation in technique between kayakers of different levels of ability. This was to be accomplished through a qualitative analysis of the motions of the whole body, paddle and kayak, and quantitative temporal analysis determining the specific areas that differ as ability level increases.

2.3. Method

2.3.1. Subjects and Procedure

One hundred and thirty-five international (n=78), national (n=38) and club (n=19) level paddlers were used as the subjects for this study. Data were collected at two separate regattas. The first filming session was at the British National Championships at Holme Pierrepont National Water Sports Centre, Nottingham in May 2004, during which the club and national level paddlers were recorded. The second filming session was at the Second World Cup, the 23rd International Canoe Regatta in Duisburg, June 2004, Germany. The informed consent of the event organisers to film the regatta was obtained. Recording of events was captured using JVC compact video recorders set at 50 Hz and positioned 1 m from the ground at 100 m from the finish line. Each camera was panned to follow an individual paddler in lanes 4 and 6, positioned approximately 150 m from the finish line.

2.3.2. Data Analysis

A qualitative review of the filmed footage was used initially as a tool for subject selection. The subject selection was determined by the clarity of the recorded image from the side, anterior and posterior view point. The quantitative temporal analysis consisted of seven variables which were determined by reviewing the video footage at 50 Hz on a Saville 21 inch colour television and a Panasonic NV-HS870 Super VHS video recorder. By counting fields (0.02 s), it was possible to determine the following temporalvariables:

a) Stroke Rate – The number of complete cycles per minute. One cycle consisting of paddle entry to paddle entry on the same side.
b) Stroke Cycle Time – Time between paddle entry and paddle entry on the left side (closest to camera).

c) Pull Time – The total time the paddle was in contact with the water during a complete stroke cycle, inclusive of both left and right sides.
d) Glide Time – The time the paddle had no contact with the water during a complete stroke cycle.
e) Pull Time as a percentage of Stroke Cycle time – the percentage of the stroke cycle that the paddle was in contact with the water.
f) Glide Time as a percentage of Stroke Cycle time – the percentage of the stroke cycle time the paddle was not in contact with the water.
g) Race Time – the time it took the competitor to complete the race distance (official race times).

In addition to the temporal variables, 22 qualitative spatial variables were measured through a ranking system between 0 and 5. Each rank was determined along the basic scale as follows

0 – none
1 – minimal, small, narrow, close
5 – excessive, wide, large.

An individual researcher completed the qualitative analysis assigning ranking scores for all subjects. The reliability of the researcher was assessed by repeated rankings of the same video footage on two occasions 4 weeks apart. On both occasions thirteen paddlers were ranked using the 22 spatial variables that follow, from which comparisons between the two sessions were carried out. To ensure there was not a significant difference between the scores recorded from each session the ranking scores were compared using a Wilcoxon related pairs test. The Wilcoxon was used as the data were non-parametric and the two sets of data were from the same set of subjects and therefore a within subjects analysis was required. Results indicated that there were no significant differences in the scores for 21 of the 22 spatial variables; only the push arm extension exhibited a significant difference when scored qualitatively in the two different session.

In addition to the Wilcoxon test the sum of the ranked scores for each individual subject was calculated from each testing session and plotted in a scatter graph onto which a regression line was plotted (figure 3.1). The R^2 value of 0.87 was produced which indicates a strong correlation between the global scores produced during each testing session. The findings of the Wilcoxon and an R^2 value of 0.87 indicate that the scores produced during each session were not significantly different and that there was a strong correlation between the scores from each of the testing session, therefore the use of a single scorer was acceptable.

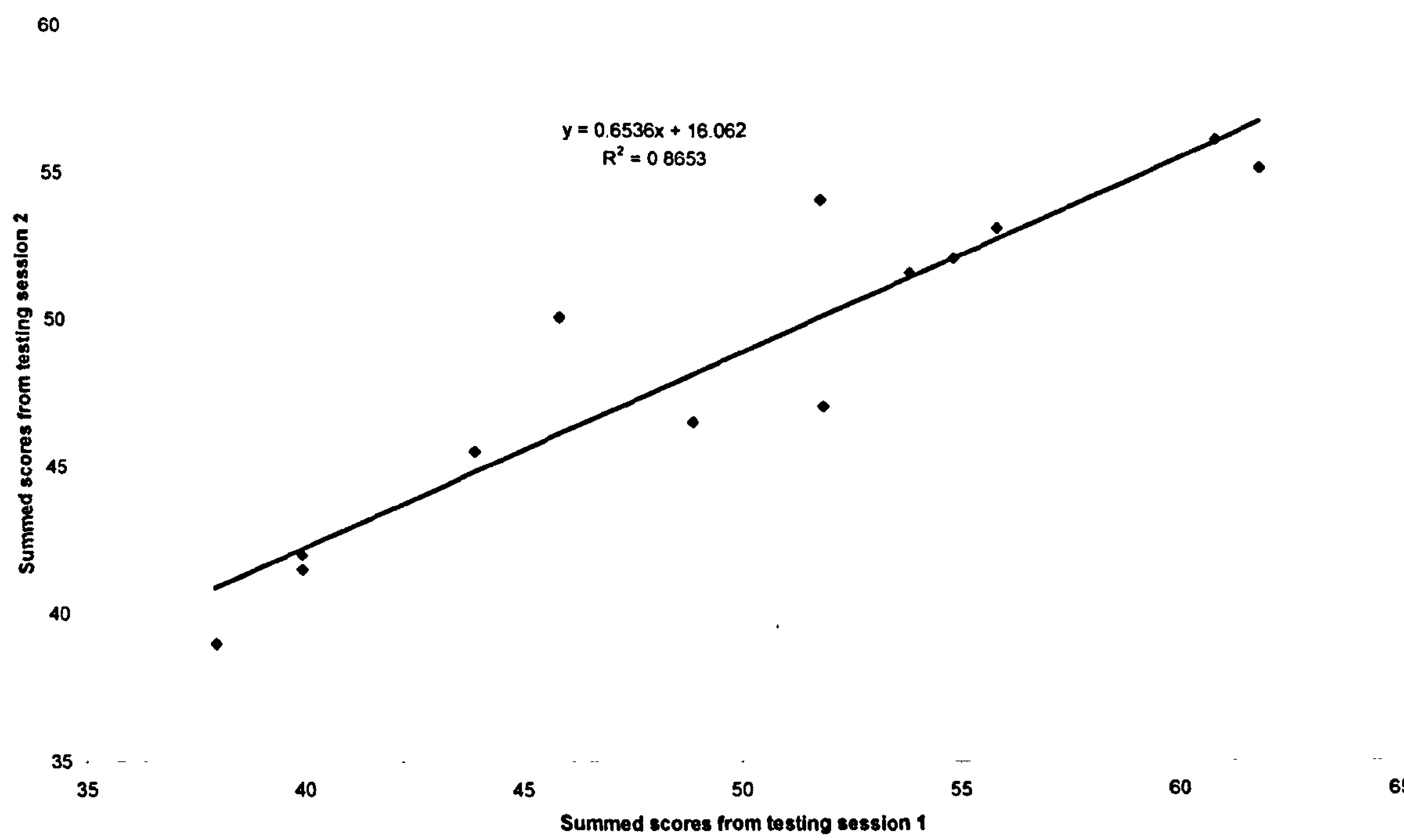


Figure 2.1. Scattergram of summed scores of subjects for accuracy assessment of researcher repeatability.

The 22 spatial variables were:

2.3.2.1. Leg Action Variables

i Leg Motion – The total amount of flexion and extension at the knees throughout the stroke cycle, contributed to by the leg extension and flexion, in addition to any lateral motion of the legs, with no motion scoring 0 and extensive motion scoring 5.

ii Leg Flexion – The degree of flexion in the knee opposite the side of the submerged blade during the pull stroke. No change in the knee angle during the pull scoring 0. The scores of 1-4 were determined by estimated half knee depth vertical movements of the centre of the knee joint. Flexion with the whole knee moving to a position above front edge of the cockpit of the kayak scored 5

iii Leg Extension – The amount of extension at the knee on the pull side, during the pull phase of the stroke. No visible attempt to extend the leg from the seated neutral position scored 0. Scores of 1-4 were determined through estimated 10° decreases in knee angle, until full extension that scored 5.

iv Arm-leg Timing – How well the extension of the leg and paddle interact – based on the premise that the best technique is to start the extension of the leg on the paddle entry side just after paddle entry (Kemecsey, 1986). Therefore a score 0 was given if knee extension started in the frame following blade entry. Scores of 1-4 were determined by the number of frames between the paddle entry and initiation of leg extension. Two fields variation either before or after the frame following blade entry scored 1, 3 fields scored 2, 4 fields scored 3, 5 fields scored 4 and 6 or more fields scored 5.

v Knee Proximity – the proximity of the knees to each other. Knees touching scored 0, scores of 1-4 were determined by estimated knee width lateral displacements, until knees touching the sides of the cockpit scored 5.

2.3.2.2. Paddle and Arm Variables

vi Paddle to Vertical – How close the position of the paddle came to the vertical in the sagittal plane during the pull phase, as Sanders and Baker (1998) suggested that when the paddle was in a vertical position, the orientation of the blade was at an optimal level to produce lift forces. The closer to the vertical the lower the score, therefore a vertical position scored 0, scores of 1-4 were determined by 15-20° movements away from the vertical, until a horizontal position scored 5.

vii Blade Entry to Centre Line – how close the paddler entered the blade to the longitudinal centre line of the kayak hull. Touching the hull of the kayak scored 0 with the ranking score increasing as the blade was entered further from the longitudinal centre line of the kayak determined by blade widths 1 blade width scored 1, 2 blade widths scored 2 continuing to a maximum score of 5 for 5 blade widths or larger.

viii Stroke Width – The amount of lateral blade motion produced during the stroke. No lateral motion scored 0 while the ranking score increased as the paddle was moved over a greater lateral distance, measured in blade widths, scored in the same method as blade entry (vii) up to a maximum of 5.

ix Grip – A combination of the left and right hand position, with the distance between the hands of the paddler and the point at which the blades attach to the shaft of the paddle. Touching the blade-shaft junction scored 0. The scores of 1-4 were determined by hand width movements toward the centre of the paddle shaft, while a grip at shoulder width scored 5.

x Push Arm Height – The height of the push arm during the recovery of the stroke in relation to the head of the paddler. Below the line of the chin scored 0, while wrist width increases in height were used to determine the 1-4 scores. Whole hand and half of forearm above head scored 5.

xi Pull Arm Flexion – The amount of flexion in the elbow of the pull arm during the pull phase of the stroke cycle, in reference to full flexion. Full flexion scored 0 with the 1-4 scores determined through 30° decreases in elbow flexion until full extension which scored 5.

xii Push Arm Extension – The amount of extension in the elbow of the push/recovery arm during the pull phase of the stroke cycle. Full extension scored 5 with the 1-4 scores determined by 30° decreases in elbow extension until full flexion which scored 0.

xiii Forward Reach – How far forward the paddle entered the water in reference to the front of the cockpit. If the blade is entered in line with the knees a score of 0 was given with scores of 1-4 given for half blade width forward increases in blade entry, with 5 scored for blade entry at approximately 0.3m in front of the cockpit.

xiv Backward Reach – How far back the paddle exited the water with reference to the line of the paddler's trunk and the back of the cockpit. If the blade exited the water before reaching the trunk then the paddler scored 0. The scores of 1-4 were determined by half blade width intervals moving backwards toward the back edge of the cockpit. If the paddle exited the water behind the back edge of the cockpit the paddler scored 5.

xv Head Motion – The total amount of rotation, lateral and forward and backward motion of the head. No movement scored 0 while excessive movement scored 5.

2.3.2.3. Boat Variables

xvi Boat Motion – The total motion of the boat defined through a contribution from the rocking (or roll) and bouncing (or pitch) actions, no lateral or vertical motion scored 0 while excessive motion scored 5.

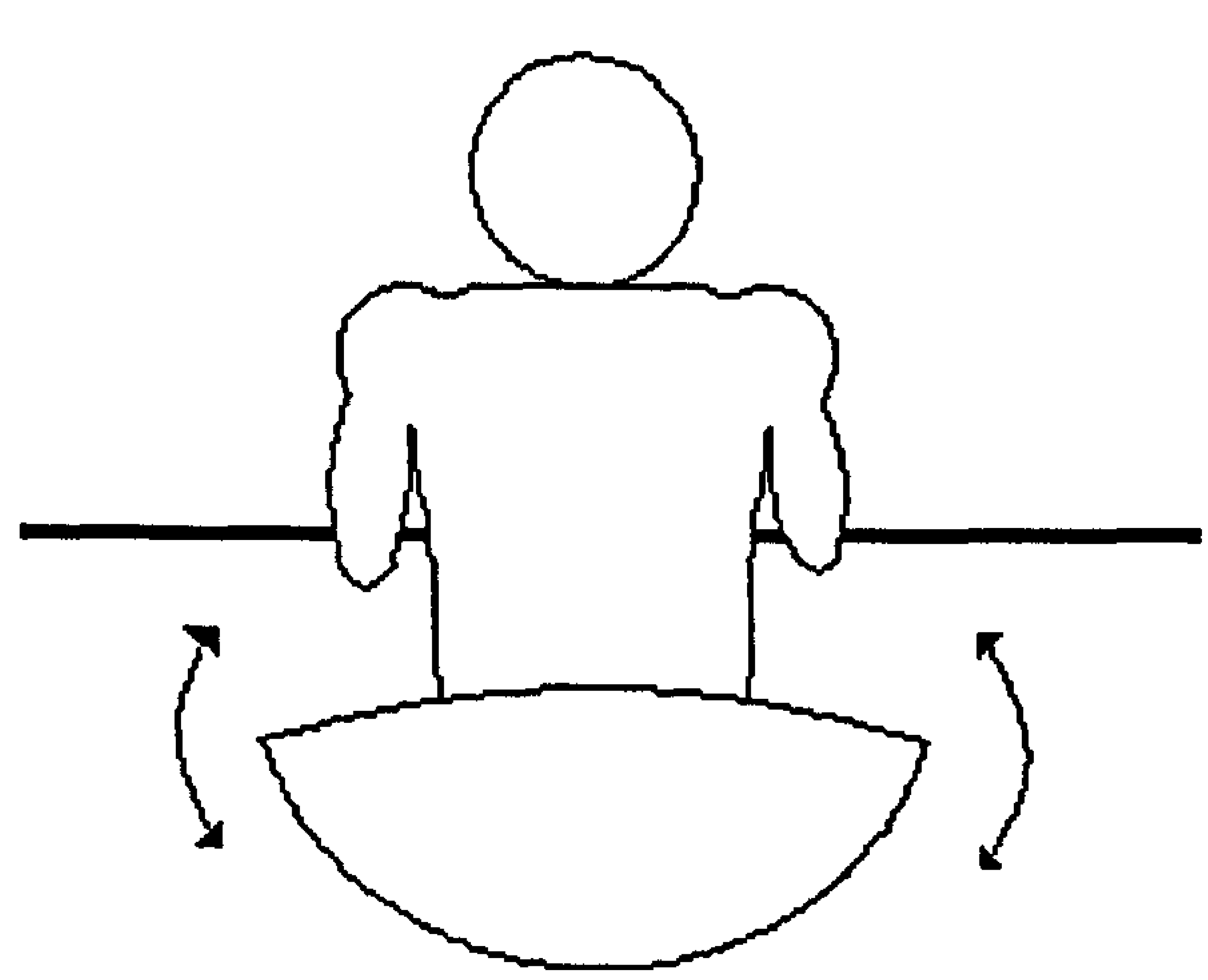


Figure 2.2. Depiction of Rocking motion of the kayak.

xvii Rocking – Rocking occurs around the longitudinal axis of the kayak with the port and starboard edges of the kayak moving up and down (figure 2.2). Scores of 0 were achieved when no motion around the longitudinal axis was exhibited, with 5 being scored for the edges of the kayak touching the waters surface due to the motion around the longitudinal axis of the kayak. (Also known as the roll of the kayak).

xviii Bouncing – Bouncing is determined by an up and down motion of the kayak during paddling, of which three types occur. (Also known as the pitch of the kayak).

1. The first type occurs around a transverse axis through the centre of the kayak whilst the bow and stern move up and down in a seesaw motion (figure 2.3).

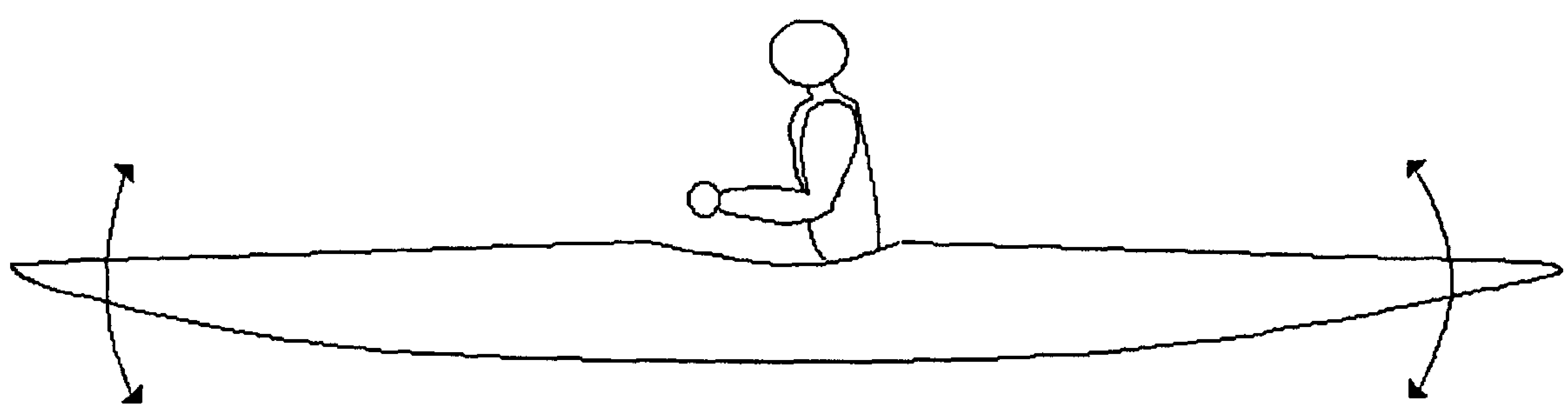


Figure 2.3. Depiction of Bouncing Type 1.

2. The second type occurs around a transverse axis through the point of the bow with the stern moving up and down (figure 2.4).

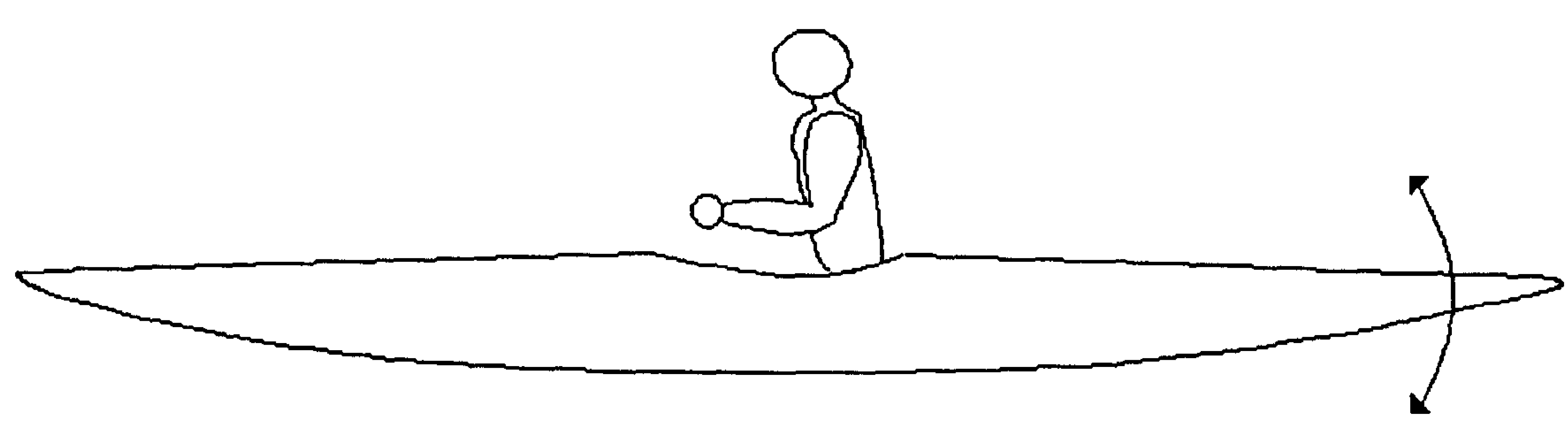


Figure 2.4. Depiction of Bouncing Type 2.

3. The third type occurs around a transverse axis through the point of the stern with the bow moving up and down (figure 2.5).

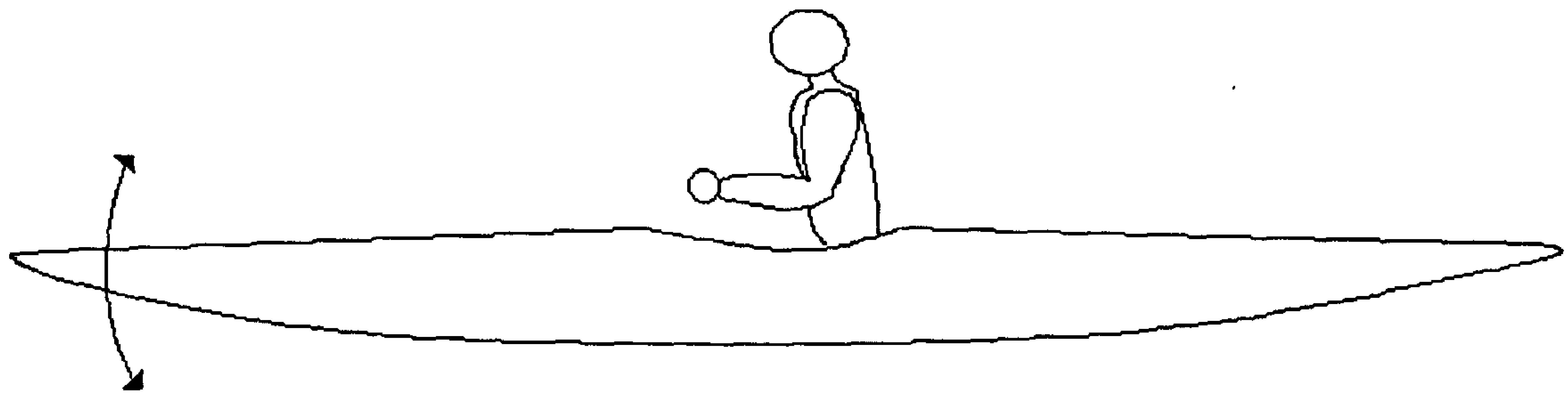


Figure 2.5. Depiction of Bouncing Type 3.

Scores for bouncing cumulative from the 3 types outlined previously, with no bouncing motions scoring 0, scores of 1-4 could be determined by the amount of the kayak that was begin submerged during the pull phase of the stroke in 0.05 m changes, while submersion to the edges of the deck of the kayak scored 5.

2.3.2.4. Trunk Variables

xix Lateral Trunk Motion – The amount of motion of the trunk from side to side, determined through the use of an imaginary line being drawn down the spinal column. No movement in this line scored 0 while the scores from 1-4 were determined by 10° changes until the line reached an approximate 50° from the vertical, this position scored 5.

xx Forward Lean – The extent to which the paddler leant forward, similarly to lateral trunk motion an imaginary line was drawn down the spinal column from which a vertical line scored 0, with the scores of 1-4 determined by 10° intervals until contact between the knees and the chest which scored 5.

xxi Change in Forward Lean – The variations within forward lean during the stroke cycle. No change from the start position scored 0, with 10° changes, in either forward or backward directions, used as interval for the scores of 1-4, 5 was scored for an approximate change by 50° or more.

xxii Trunk Rotation – The extent to which the trunk rotated, if the shoulders were judged to stay parallel to the hips then 0 was scored, the scores of 1-4 were determined though 15-20° variations from the parallel position until a perpendicular position between the shoulders and hips for which 5 was scored.

2.3.3. Statistical Analysis

The paddlers were initially divided into ability levels of international, national, and club level. The groups were determined by the standard that they were competing at, i.e. paddlers from the Duisburg regatta were all classed as international paddlers, while the paddlers from the A/B class and C/D class at the BCU National Championships were determined to be national and club level, respectively. Male and female paddlers were analysed together for the spatial variables in conjunction with Baker *et al.*'s (1999) findings that male and female paddling techniques were not significantly different ($P > 0.05$). The spatial variables for the paddlers from the 200 m and 500 m were also analysed together as both distances are classified as sprint events by the ICF. For the analysis of the temporal variables males and females were not analysed together, neither were the 200 m and 500 m events. This grouping was performed as the times for the events and genders are clearly different (see table 2.2).

The analysis of the paddlers from the footage collected produced both parametric (temporal variables) and non-parametric (spatial variables) data, therefore two different statistical analyses were required. Initially a one-way analysis of variance (ANOVA) was utilised to determine significant differences between the temporal variables of the international, national and club level paddlers. Significant differences highlighted by the ANOVA were followed up with pairwise comparisons using a Tukey post hoc test to determine the specific significant differences between the ability levels.

Furthermore, a Kruskal-Wallis analysis was used to identify the significant differences ($P < 0.05$) in the spatial variables between the international, national and club paddlers. The rationale for this was the ranked data was best suited to a non-parametric statistical analysis as the data were ordinal data, therefore parametric tests were not applicable. Significant differences highlighted by the Kruskal-Wallis were further investigated through the use of Mann-Whitney U tests, with a Bonferroni adjustment of the α level to 0.02. The Bonferroni adjustment was used to reduce type I errors experienced when making repeated use of the same data set. The Mann-Whitney U tests were used to determine the exact point of the significant differences found between the international, national and club groups in the Kruskal-Wallis test

2.4. Results

2.4.1. Temporal Variables

Male international paddlers produced significantly faster times than the national paddlers over 200m and were faster than the national and club paddlers over 500 m. International female paddlers were significantly faster than their club counterparts over 200 m and significantly faster than the national and club paddlers over the 500 m. Both the male and female national paddlers were significantly faster than the club level paddlers over the 500 m (table 2.2).

Table 2.2. Descriptive statistics of the 200 m and 500 m race times.

Variable			Time (s)			
Distance			200 m		500 m	
			Mean	SD	Mean	SD
International	Male	(n = 46)	*38.95	0.56	*†98.77	4.53
	Female	(n = 32)	†44.45	1.33	*†112.06	6.69
National	Male	(n = 29)	43.70	3.51	^113.72	7.72
	Female	(n = 9)	48.17	3.61	^121.81	5.96
Club	Male	(n = 9)	-	-	134.38	8.41
	Female	(n = 10)	51.70	3.43	144.96	4.73

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers. $P < 0.02$

The temporal variables were analysed separately as inspection of the mean times indicated that the males were faster than the females and the mean times for the 200 m were faster than the 500 m (table 2.2). Furthermore previous research has also indicated the time differences between gender and race distance (Hay and Kaya, 1998: and Baker *et al.*, 1999).

Statistical analysis using the ANOVA and Tukey post hoc indicated a number of significant differences. For the male 500 m analysis the international paddlers exhibited significant differences to national and club level paddlers in stroke rate, stroke time and pull time. A further significant difference between international and national paddlers in glide time was identified (table 2.3). Comparison between the national and club paddlers in the 500 m event revealed the national utilised significantly faster stroke rate, stroke time and glide time. Whilst further significance was found between the national and club paddles in the pull percentage of total stroke and glide percentage of the total stroke cycle.

Table 2.3. Descriptive statistics of the temporal variables for the male 500 m event.

Variable	International		National		Club	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Stroke Rate (S/min)	*†60.49	3.23	^56.29	3.58	50.23	4.90
Stroke time (s)	*†0.99	0.06	^1.07	0.07	1.2	0.12
Pull Time (s)	*†0.56	0.06	0.61	0.06	0.63	0.09
Glide Time (s)	†0.44	0.06	^0.46	0.04	0.57	0.07
Pull % of total stroke	56.1	5.19	^57.5	3.68	52.7	4.31
Glide % of total stroke	43.9	5.24	^42.5	3.68	47.3	8.42

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P < 0.02$.

The temporal variables for the male paddlers over the 200 m event (table 2.4) displayed similar findings to the 500 m event (table 2.3). The male 200 m only had two ability groups, international and national, between which significant differences in the stroke rate and stroke time were identified. However in the 200 m, the glide time was significantly different between the abilities, unlike the 500 m where a significant difference in pull time was demonstrated (tables 2.3 and 2.4).

Table 2.4. Descriptive statistics of the temporal variables for the male 200 m event

Variable	International		National	
	Mean	SD	Mean	SD
Stroke Rate (S/min)	*68.92	3.37	60.65	4.71
Stroke Time (s)	*0.87	0.04	0.99	0.07
Pull Time (s)	0.48	0.05	0.49	0.09
Glide Time (s)	*0.39	0.05	0.50	0.08
Pull % of Total Stroke	55.4	4.98	49.4	8.14
Glide % of Total Stroke	44.6	4.98	50.6	8.14

The symbols denote significances between ability level with * denotes significance between international and national paddlers, $P \leq 0.02$.

Tables 2.5 and 2.6 provide the temporal variable descriptive statistics for the women's 500 m and 200 m events, respectively. Significant findings in the 500 m were confined to stroke rate, stroke time and glide time between the club and international paddlers and stroke time and glide time between club and national paddlers. There were no significant differences found between any of the ability levels over the female 200 m (table 2.6).

Table 2.5. Descriptive statistics of the temporal variables for the female 500 m event.

Variable	International		National		Club	
	Mean	SD	Mean	SD	Mean	SD
Stroke Rate (S/min)	†57.41	4.16	57.82	3.16	50.86	4.89
Stroke time (s)	†1.05	0.08	^1.04	0.06	1.19	0.11
Pull Time (s)	0.57	0.05	0.57	0.06	0.59	0.05
Glide Time (s)	†0.48	0.05	^0.47	0.02	0.60	0.11
Pull % of total stroke	54.07	2.74	54.51	3.09	50.07	5.75
Glide % of total stroke	45.93	2.74	45.49	3.09	49.93	5.75

The symbols denote significances between ability level with † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P < 0.02$.

Table 2.6. Descriptive statistics of the temporal variables for the female 200 m event.

Variable	International		National		Club	
	Mean	SD	Mean	SD	Mean	SD
Stroke Rate (S/min)	64.06	5.41	58.93	2.99	57.21	4.69
Stroke time (s)	0.94	0.08	1.02	0.05	1.05	0.08
Pull Time (s)	0.47	0.05	0.55	0.02	0.53	0.06
Glide Time(s)	0.47	0.04	0.47	0.04	0.52	0.04
Pull % of total stroke	49.6	4.84	53.9	1.7	50.6	2.75
Glide % of total stroke	50.4	4.84	46.1	1.7	49.4	2.75

2.4.2. Spatial Variables

Table 2.7. Descriptive Statistics of the leg variables across ability levels.

Variable	International			National			Club		
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range
Leg Motion	†3.2	3	2-4	^2.9	3	1-4	2.2	2	0-4
Leg Flexion	†3.2	3	2-5	^2.9	3	0-4	2.2	2	0-4
Leg Extension	*†3.3	3	1-5	2.8	3	0-4	2.3	2	0-4
Knee Proximity	*†2.0	2	1-3	2.4	2	0-3	2.7	3	0-4
Arm-leg Timing	*†1.7	2	1-3	^2.0	2	0-4	2.8	3	0-4

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P < 0.02$.

Males and females spatial measures were analysed together in accordance with Baker *et al.*'s (1999) findings, indicating that techniques used by males and females were not significantly different. From the initial analysis a large number of significant differences were apparent in the spatial variables of technique for the international, national and club level paddlers.

Table 2.8. Descriptive Statistics for the paddle and arm variables across ability levels

Variable	International			National			Club		
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range
Paddle to vertical	†2.0	2	1-4	^2.3	2	1-5	3.2	3	2-4
Blade entry to centre line	†1.7	2	1-3	^1.9	2	1-3	2.2	2	1-3
Stroke Width	*†2.9	3	1-4	^2.5	3	1-4	2.0	2	1-3
Grip	2.4	2	1-4	2.7	2	1-4	2.3	2	1-4
Push Arm Height	†3.4	3	0-5	^3.4	3.5	2-5	2.6	3	0-5
Pull Arm Flexion	3.5	4	2-5	3.5	4	2-5	3.0	3	1-4
Push Arm Extension	2.5	3	1-3	2.7	3	1-4	2.6	3	1-4
Forward Reach	*†3.0	3	2-5	2.6	3	1-4	2.2	2	1-4
Backward Reach	2.3	2	1-4	2.6	3	1-4	2.6	3	1-4
Head Motion	0.7	1	0-2	0.8	1	0-3	1.1	1	0-3

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P < 0.02$.

Table 2.7 provides descriptive statistics for the leg variables clearly indicating international paddlers' higher mean scores for leg motion, flexion and extension. These variables were all found to be significantly higher than the club level paddlers. The leg extension, knee proximity and arm-leg timing were found to be significantly different between the national and international paddlers and international and club paddlers. Differences between the national and club levels were highlighted in the leg motion, leg flexion and arm leg timing variables. Inspection of the ranges indicate that the international paddlers' scores were more closely grouped, as in general the range was smaller than the national and club paddlers. This may be an indication that the international paddlers were more consistent in the use of the legs in their technique with closer timing of arm and leg actions.

The paddle and arm variables displayed only two significant differences between the international and national paddlers, these being in the stroke width and the amount of forward reach (table 2.8). Significant differences between the international and club level paddlers occurred across a number of measures; the paddle to vertical, blade entry, stroke width, push arm height and forward reach. Differences between national and club paddler were found for the paddle to vertical, blade entry, stroke width and push arm height. All other measures were found to be not significantly different between ability levels.

Table 2.9. Descriptive statistics for the trunk variables across ability levels.

Variable	International			National			Club		
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range
Lateral Trunk Motion	1.2	1	0-3	1.1	1	0-2	1.3	1	0-3
Forward Lean	1.3	1	0-4	1.4	1	0-3	1.7	2	1-3
Change in forward Lean	†0.2	0	0-3	^0.2	0	0-2	0.8	1	0-4
Trunk Rotation	*†2.8	3	1-4	^2.4	2	0-4	1.8	2	0-4

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P < 0.02$.

The measures of trunk motion showed no significant differences at any level for lateral trunk motion or forward lean (table 2.9). However, the club paddlers differed significantly from the international and national paddlers in the change in forward lean, exhibiting a greater change than the higher abilities. The final variable, trunk rotation, was found to be significantly different between all levels of ability, with the international exhibiting the highest and the club the lowest mean score for trunk rotation. The range of scores in the trunk rotation indicated that the international paddlers ranks were more closely grouped than their national and club counterparts, possibly suggesting that there was a more consistent use of the trunk rotation within international level paddling technique.

Table 2.10. Descriptive statistics for the boat variables across ability levels.

Variable	International			National			Club		
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range
Boat Motion	*†1.3	1	0-4	^1.7	2	0-4	2.7	3	0-4
Rocking	*†1.2	1	0-3	^1.5	1	0-4	2.7	3	0-4
Bouncing	†1.0	1	0-4	1.5	1	0-4	2.2	2	0-4

The symbols denote significances between ability level with * denotes significance between international and national paddlers, † denotes significance between international and club paddlers, ^ denotes significance between national and club paddlers, $P \leq 0.02$.

All boat measures presented significant differences between ability levels (table 2.10). The mean scores showed international paddlers demonstrated the smallest boat motion and the club the highest. The only exceptions were in bouncing motion between the international and national and the national and club levels, where no significant differences were found. The ranges of ranking scores for all the boat variables were identical across every level (0-4) except for the rocking in the international paddlers (0-3) (appendix A raw data and SPSS output).

2.5. Discussion

2.5.1. Temporal Analysis

Initial inspection of results confirmed some previous expectations in that the international paddlers produced significantly faster race times than the national paddlers. However an unexpected finding was for the female 200 m paddlers who did not follow this trend with the international and national paddlers times not exhibiting a significant difference. International paddlers also produced significantly faster times than club level paddlers in the 500 m event. In the 200 m event a significant difference was identified between race times for female international and club paddlers while male paddlers did not compete over 200 m at club level. Furthermore the national paddlers exhibited significantly faster times than the club paddlers over the 500 m distance, but the female club and national level paddlers 200 m race times were not significantly different.

Previous research has indicated that stroke rate is the most important determinant of boat speed and therefore race time (Kerwin *et al.*, 1992; Sanders and Kendal, 1992; Hay and Kaya, 1998). Significant differences were found between the male international and national paddlers' stroke rates for both 200 m and 500 m events, between the international and club paddlers for the 500 m event and between the national and club level paddlers in the 500 m event (tables 2.3 and 2.4). No significant differences were found between female paddlers in the international, national and club level 200 m paddlers. Kerwin *et al.* (1992), Sanders and Kendal (1992) and Hay and Kaya (1998) findings that stroke rate was the most important factor in performance and therefore ability level are in agreement with the current study, however, only when comparisons between international and national/club paddlers are performed. It would appear that stroke rate is not sensitive enough to determine differences in all event distances at lower ability levels (national and club).

In addition to investigating the race time and stroke rate the percentage of the total stroke time contributed by the pull and glide phases also displayed a number of interesting differences across all ability levels, in particular glide time. The international male paddlers in the 200 m event (table 2.4) exhibited a significantly shorter glide time than the national paddlers (Int. 0.39 ± 0.05secs, Nat. 0.50 ± 0.08 secs). Furthermore the male international (0.44 ± 0.06 secs) and national (0.46 ± 0.04 secs) paddlers also displayed significantly lower glide times than the club (0.57 ± 0.07 secs) paddlers over the 500 m event (table 2.2), which was again mirrored in the female 500 m events with the national (0.47 ± 0.02 secs) and international (0.48 ± 0.05 secs) paddlers having significantly lower glide times (Club 0.60 ± 0.11 secs; table 2.5). This may indicate that this is a key factor within kayaking performance as it is during the glide phase that average boat velocity decreases (Sanders and Kendal, 1992a). Hence it appears the higher ability paddlers reduce glide time, therefore, maintaining a higher average boat velocity.

The pull time was found to be non significant in all but one case, in which male club paddlers displayed significantly longer pull times than their international counterparts, however further analysis of this indicates this was a direct result of an increased stroke time. Inspection of the female 500 m data (table 2.5) shows that both the pull time and glide time percentages are significantly different between the international (Pull 54.1 ± 2.7 %, Glide 45.9 ± 2.7 %) and club (Pull 50.1 ± 5.8 %, Glide 49.9 ± 5.8 %) paddlers, clearly indicating a longer pull time percentage in international technique. Furthermore if pull time percentages are investigated in males (Male: Int. 56.1 %, Nat. 57.5 %, Club 52.7 %), clearly the international and national paddlers keep the paddle in contact with the water for a greater percentage of cycle time.

2.5.2. Spatial Analysis

Despite the temporal variables being analysed and assessed in separate gender and event groups, the spatial variables of technique were analysed as a large group. The rationale for this was developed from Baker *et al.*'s (1999) findings that the male and female techniques were not significantly different and that the 200 m and 500 m both constituted sprint events and so were grouped together.

International versus National

From the statistical analysis several significant differences were established between the international and national level paddlers. Initial inspection of the (table 2.7) results indicated no difference in the extent of overall leg motion between the international paddlers (mean: 3.2) and the national paddlers (mean: 2.9). Overall leg motion, however, is not the only key factor as the extent to which the legs are flexed and then extended is also of interest. In both cases the international paddlers displayed a greater degree of motion, with the leg extension found to be significantly different. No significantly different finding for leg flexion between the international and national paddlers was found despite the international paddlers (mean: 3.2) exhibiting higher flexion than the national paddlers (mean: 2.9). This could indicate that the extension of the legs is an important factor within elite level performance as it could be the driving force developed during the straightening that enables an effective production of the force during the stroke.

The proximity of the knees was another significant difference between the international and national paddlers shown in table 2.7, with the international paddlers (mean: 2.0) keeping their knees closer together than the national paddlers (mean: 2.4). This finding indicated that the legs were kept closer and more parallel in reference to the centre line of the longitudinal axis of the kayak by the international paddlers and would result in a reduction in loss of force laterally, which would reduce excess boat motion (as seen in international paddlers boat motion values table 2.10), therefore ensuring higher efficiency levels in kayak propulsion. If the legs are bowed, this could result in some force being lost in a lateral direction causing a rocking motion of the kayak, indicated by the significantly higher gap between the national paddlers' knees and the significantly higher levels of rocking (Int. mean: 1.2, Nat. mean: 1.5) and boat motion (Int. mean: 1.3, Nat. mean: 1.7). The timing between the legs and the arms and paddle was found to be significantly closer within the international level than the national level; once again re-enforcing the apparent importance of the legs within elite level paddling technique as initially identified by Kemecsey (1986). The range of the ranking scores in the knee proximity and arm-leg timing was smaller than that of the national paddlers indicating that there was a grouping of the scores. This may signify that the international paddlers' techniques are more alike than those of the national level, which indicate a greater range of variations in technique.

The timing of the arms and legs is not the only important variable relating to the arms and paddle, as the positioning of the arms and paddle will allow the performer to gain the most efficient use of the aerofoil blade design. Many previous researchers have determined that the near vertical position the blade achieves during the power maintenance phase is very important within paddling technique (Plagenhoef, 1979; Mann and Kearney, 1980; Kerwin *et al.*, 1992; Sanders and Baker, 1998). Inspection of the vertical position of the paddle indicated that the international paddlers (mean: 2.0) produced a closer to vertical position of the paddle than the national paddlers (mean: 2.3) although this difference was not significant. However, significant differences were identified in the stroke width between the international and national levels, with the international paddlers moving the paddle laterally a greater distance than the national level (table 2.8 - Int. mean: 2.9, Nat. mean: 2.5). This increased lateral motion is despite the non-significant findings in the point of blade entry, however the greater stroke width may have been a result of the point of blade entry being significantly further forward in the techniques exhibited by the international paddlers. There were no significant findings in the backward reach therefore, suggesting that the increased forward reach shown by the international paddlers is important to the larger stroke width providing a longer lateral distance that the paddle can be moved.

The orientation of the arms during the stroke did not highlight any significant differences in the techniques of the international and national paddlers with the grip, extension of the push and flexion of the pull arms, and the height of the push arm all exhibiting non significance. The final variable incorporated in the arm and paddle section is the motion of the head, which was found not to be different with both national and international paddlers displaying little head motion. Similarly to the arm and paddle variables all the trunk variables, with the exception of trunk rotation, exhibited no significant differences. The significant finding in the mean values of trunk rotation (table 2.9) within the paddling techniques of the international paddlers (2.8) in comparison to 2.4 for the national paddlers, supported Kemecsey's (1986) indication that the rotator muscles and the rotation of the trunk are important in kayaking performance.
The boat motion variables all indicated significantly less boat motion in the international level paddlers. The rocking level was found to be significantly higher (rocking, Int. 1.2, Nat. 1.5 and bouncing, Int. 1.0, Nat. 1.5) in the national paddlers. One key factor that possibly may have effected this is the knee proximity, as if the legs are bowed (i.e. further apart) with the knee pointing outward some force may have been directed in a lateral direction causing the kayak to rock causing a reduction in boat velocity and an increase race time.

The comparison between the international and national level paddlers has identified a number of key factors that may be the key to higher performance levels. However further comparison between the international and club, and national and club are important to determine if the patterns of significance occur throughout the ability levels.

International versus Club

A large number of significant differences were identified between the international and club paddlers within the leg movement variables (table 2.7). The leg motion of the club paddlers (Club mean: 2.2) was significantly less than that of the international paddlers with the leg flexion and extension also displaying significant differences. This may suggest that the increased utilisation of the legs is a determinant of higher performance levels, mirroring the results of the international/national comparison. Furthermore the international paddlers again exhibited a closer knee proximity than the club paddlers, as well as better interaction of the legs with the paddle and arms. These findings further support the findings highlighted in the international/national comparison, suggesting that the legs are more important than previously acknowledged in the literature.

Analysis of the paddle and arm variables (table 2.8) reveal further insight into the technique differences between ability levels. International paddlers produced a paddle angle significantly closer to the vertical than the club paddlers, therefore producing a more efficient application of the wing blade (Sanders and Baker, 1998). This vertical position and greater use of the wing paddle design was supported by a number of other significant findings between the international and club paddlers. The point of blade entry was closer to the centre line as well as a greater forward reach, allowing a significantly wider stroke. In conjunction with these the height of the push/recovery arm also displayed significant differences. The international paddlers had higher push/recovery arm position (Int. mean: 3.4) than the club paddlers (Club mean: 2.6). Furthermore the international paddlers exhibited less flexion in the pull arm (Int. mean: 3.5) than the club level (Club mean: 3.0), although this was not significant. The higher push arm height would allow the paddler to create a more vertical position with the paddle, while the straighter pull arm would assist in increasing the width of the stroke as a straight arm would allow the blade of the paddle to be moved further from the kayak.

There were no significant findings in the extension of the push arm indicating that the extension of the push/recovery arm is not a determinant of ability level. In addition to this the position of the grip and backward reach during the stroke cycle did not indicate any significant differences either, along with the motion of the head. The non significant findings in head motion are surprising when compared with the trunk variables, with half of the trunk variables indicating significant differences between levels. The club level paddlers exhibited significantly greater changes in the degree of forward lean throughout the race (table 2.8 - Int. mean: 0.2, Club mean: 0.8). Further comparison of trunk rotation were analysed indicating the international paddlers (Int. mean: 2.8) displayed significantly higher levels of trunk rotation than the club paddlers (Club mean: 1.8). This would indicate, that as in the case of the national paddlers, the international paddlers used the trunk rotator muscles more effectively than the club paddlers. The final trunk variable, lateral trunk motion, indicated no difference between the international and club paddlers with both ability groups exhibiting low levels (Int. mean: 1.2, Club mean: 1.3).

Comparison between the boat motions of the international and club paddlers presented several further significant differences. The club paddlers' scored significantly higher than the international paddlers in overall boat motion (Int. mean: 1.3, Club mean: 2.7), rocking (Int. mean: 1.2, Club mean: 2.7) and bouncing (Int. mean: 1.0, Club mean: 2.2). These could have been caused directly from other factors within the technique. The rocking by a larger distance between the knees therefore losing force in a lateral direction. The bouncing may have been caused by the constant changes in the degree of forward lean as the forward and back motion of the trunk is likely to have been transferred to the kayak (Kemecsey and Lauder, 1998).

Clearly there are differences between the techniques employed by international and club paddlers, which appear to have an effect on performance when event times are compared. A comparison of national and club paddlers will provide performance markers for the lower abilities to aspire toward.

National versus Club

The pairwise comparisons from Tukey post hoc tests comparing the national and club level paddlers presented similar findings to those between the international and club paddlers. The national paddlers' technique displayed significantly greater leg motion than the club paddlers (table 2.7 - Nat. mean: 2.9, club mean: 2.2). This was prominent in the amount of leg flexion, with the national paddlers exhibiting higher levels than the club paddlers (Nat. mean: 2.9, Club. Mean: 2.2). The arm and paddle timing to the legs was found to be significant with the national paddlers having better timing than the club paddlers, indicating a better interaction between the upper and lower body.

The variables assessing the motion of the arms and the paddle displayed a number of interesting results. Once again the higher ability national paddlers positioned the paddle significantly closer to a vertical position than the club paddlers, as did the international paddlers (table 2.9). This paddle position was assisted through a significantly higher push/recovery arm position and a blade entry point significantly closer to the centre line of the kayak. The blade entry point also allowed a greater stroke width to be produced by the national paddlers (Nat. mean: 2.5) despite not being significant (Club mean: 2.1). A non significant finding in the flexion of the pull arm brings into doubt the indication previously highlighted, that an extended pull arm assists in widening the stroke. As with knee proximity, the low levels of pull arm flexion could be a key determinant of international paddlers and not of lower ability paddlers.

There was no significant difference in the position of the grip between the national and club level paddlers, suggesting that the grip is not a sensitive enough measure to determine between ability levels. This again is true for the extension of the push/recovery arm, backward reach, and head motion. Furthermore forward reach was found not to differ between the national and club level paddlers where before differences had been identified between international and national and international and club paddlers. This may indicate that forward reach may not be sensitive enough to determine between all ability levels, but it may be an important determinant of elite level paddling.

The trunk motion variables reinforced the previous findings of both the current thesis and the suggestions of other researchers (Mann and Kearney, 1992; Kemecsey, 1986; Baker *et al.*, 1999). The trunk rotation (table 2.9) was once more found to be significantly different, with the national paddlers displaying more trunk rotation (Nat. mean: 2.4) during paddling technique than the club paddlers (Club mean: 1.8). This suggests a greater contribution from the rotator muscles of the trunk. Another significant difference was identified in the change in the degree of forward lean between the national and club paddlers, the club paddlers producing a higher mean score (Nat. mean: 0.2, Club mean: 0.8).

The higher mean scores for change in forward lean may have contributed to the differences found in the comparison of boat motions between the national and club paddlers. Boat motion was significantly higher in club paddlers. Further investigation into the components identified this was due mainly to the significantly higher levels of rocking, as the mean scores for the bouncing variable were not significantly different. This did not support the suggestion that changes in forward lean could be the cause of the bouncing action identified in the comparison between international and club paddlers, but does indicate the importance of the link between the body and the boat.

Although significant differences have been identified there may have been a number of limitations in the current study. The subjective nature of the rating scores could be argued to be unreliable. However the repeatability was determined through repeated scoring on two occasions to ensure the scoring system was the same. It was felt that the use of a coach was not required at this point as they may believe in specific prerequisites for performance that may differ from other coaches. It was therefore decided that a fresh eye that would be unbiased toward technique may provide the best objective analysis of technique.

2.6. Conclusions

Improvement of technique and therefore performance is a key factor in the long term progression of all flatwater kayak paddlers and although much work has measured performance and technique no other research has attempted to identify the key determinates of technique between ability levels. The findings of the current study highlight a number of key differences in the techniques of the three ability levels, international, national and club. These findings provide the lower ability paddlers with key markers of better technique, which can be used to improve performance.

The key factors in technique that differentiate the international paddlers from the national and club paddlers stem from 3 main areas. Firstly, as identified by early researchers (Hay and Kaya, 1998;, Kerwin *et al.*, 1992; Sanders and Kendal, 1992a) the stroke rates were found to be significantly higher for the international paddlers which coincided with significantly lower race times, therefore proposing that high stroke rates and low race times are determinants of ability.

Secondly the international paddlers incorporate greater use of the large muscles of the trunk and legs in their technique. This was indicated in greater rotation of the trunk in the international paddlers. The motion of the legs was also found to be greater between the international paddlers and the club paddlers and although no significance was identified between the international and national paddlers, the international paddlers' average for leg motion was higher than the national paddlers (mean 3.2 and 2.9, respectively). More specifically the extension of the legs was found to be significantly greater in the international paddlers' technique. The driving force that is produced in the straightening of the leg could be an important determinant of ability level as well as being a key factor within performance. The motion of the legs was not the only important factor within the lower body, as the position of the legs also proved to be an important difference between the ability levels. The international paddlers kept their knees and therefore legs closer together, resulting in the resistive base of force production applying the force centrally down the longitudinal axis of the kayak and reducing unnecessary boat motion. These findings indicate that elite performance requires close leg positioning and relies upon the large muscle groups of the trunk and legs being used to aid in the development of propulsive force. This is further characterised by little lateral or vertical kayak motion.

Finally the stroke characteristics of the international paddlers was found to be different to the national and club paddlers. International paddlers enter the blade closer to the centre line of the kayak supported by Sanders and Kendal (1992a), which in turn allows the paddler to position the paddle closer to the vertical. This allows the blade to be positioned to take maximal advantage of the aerofoil design. In conjunction with this the international paddlers enter the blade further forward providing a greater distance over which lift forces can be generated. All these factors contribute to a greater stoke width. International paddlers were therefore characterised by a blade entry further forward, close to the kayak, with the paddle moving to a vertical position which is then moved laterally away from the kayak.

The findings from the current study have identified that there are significant differences in the techniques employed by paddlers at club, national and international level. Furthermore data highlighted that the international level paddlers appeared to use the entire body during technique making greater use of the trunk and legs in conjunction with the upper limbs, thus providing support to the main thesis rationale concerning the importance of whole body inclusion within technique. In addition to this results from the notational analysis of technique provide further rationalisation for future research into the application of the entire body and specifically the legs and trunk during paddling technique, as conducted in the later chapters. The final implication to be drawn from this initial study concerns the subject base to be used in future research. The international paddlers' range of scores and standard deviations indicated that technique varied less between subjects than that of the lower ability paddlers. Therefore, all further testing in the current research thesis will be carried out using international paddlers, as greater similarity within technique will afford greater confidence in the application of any future findings to the general paddling population.

3. Development of On-Water Movement Recording Protocols for Kayaking.

3.1. Introduction

Recording of data in a water based environment requires the adaptation of existing land-based procedures and often the use of specialised equipment which is designed to withstand water ingress. As a result every effort must be made to ensure that all human data recording systems are safe for use in the damp and possibly water splash or immersion environment, whilst ensuring systems are optimised to guarantee successful data acquisition and analysis.

In order to achieve the aims of this research a video recording technique was adapted to allow on-water three dimensional calibration and recording of kayak paddling. The particular interests of this research, the contributions of the trunk and leg movement within effective kayak paddling performance, meant that it was essential that movement of the legs was recorded. This could not be undertaken with kinematic video recording because the legs were not visible within the hull of the kayak. Special waterproof joint angle measurement sensors and trunk rotation sensors were assessed for accuracy when used in conjunction with miniature synchronizable data logging systems, which could be worn safely by the kayakers without disruption of their paddling technique. The latter movement data would then be assessed in relation to muscular activity, also to be recorded on the data loggers. Such integrated monitoring of human movement required accurate positioning of all sensors and transducers using methods which did not disrupt movement or technique. The above requirements were addressed during reviews of existing technical knowledge and a series of pilot studies which attended to, in particular, practical feasibility, calibration, synchronisation and assessment of the data from the different recording systems.

3.2. Aim

The aim of the pilot studies were to determine the feasibility of use and accuracy of the EMG, torsiometer, electrogoniometry and three dimensional kinematic systems in the kayaking environment.

3.3. Electromyography

3.3.1. Review of technical aspects of EMG applicability.

Electromyography is a technique for the measurement of the changes in the electrical potential occurring within the muscle which is associated with contraction and is the only objective method of assessing when a muscle is active (Grieve, 1975). Although clinical biomechanics can deal with measurements as small as the changes in potentials of single muscle fibres, sports biomechanics deals with the action potentials from large numbers of motor units throughout the muscle of interest.

Previously the application of electromyography (EMG) within the area of kayaking has been limited to land based ergometers. A key problem with the use of EMG is the application of the electrodes in a water-based environment. Logan and Holt (1985) used EMG to identify the muscles that were used when paddling on an ergometer. Furthermore Logan and Holt (1985) identified the patterns in which the muscles were recruited within the entirety of the technique. Tokuhara *et al.* (1987) investigated the use of EMG as a feedback tool during specific weight training exercises that mimic the pull motion within paddling technique. Tokuhara *et al.* (1987) found that the use of EMG during a single arm pull, inclusive of trunk rotation and hip and knee extension, was a useful feedback tool and that the single arm pull movement would be a good training exercise for kayakers attempting to produce greater force during each stroke.

The findings of the notational analysis of sprint kayaking technique (Chapter 3) further supported Logan and Holt (1985), Shepherd (1987) and Kemecsey (1986) suggestion of the trunk and legs contributing to high level performance. Although previous research has been conducted into kayaking muscle activation with a focus upon paddling technique (Logan and Holt, 1985), and from a strength training perspective (Tokuhara *et al.*, 1987), consideration of further related research literature is appropriate. A review of studies investigating the activation of the trunk and leg muscles during trunk rotation and cyclical leg motion may provide assistance in the selection of an effective testing protocol. Kumar *et al.* (2002) investigated the pattern, magnitude and phasic inter-relationship of the trunk muscles during maximal and graded isometric axial rotations in comparison with dynamic conditions following the same testing protocol. Kumar *et al.* (2002) utilised back injuries as a point of focus, highlighting that the contribution of trunk rotation to lower back injuries was reported to be around 60% (Manning *et al.*, 1984). Healthy male (n = 27) and female (n = 23) subjects were prepared with passive silver-silver chloride electrode spaced at 0.02 m on the external oblique, internal oblique, rectus abdominus, pectoralis major, latissimus dorsi and the erector spinae at both the

T10 and L3 levels with sampling at 1000Hz. Subjects then performed a maximal voluntary contraction (MVC) followed by randomised 25, 50 and 75% efforts, which was downloaded directly to computer from which root means squared (RMS) EMGs' were produced.

Results indicated that the contralateral external obliques and the ipsilateral latissimus dorsi were the primary rotators of the trunk during graded axial rotations. Kumar *et al.* (2002) further identified that there were proportional increases in erector spinae activation at both the T10 and L3 regions and proportional increases in rectus abdominus activation during graded axial rotations, leading the authors to propose that these muscles performed a stabilising role during rotation. Kumar *et al.*'s (2002) study has limited applicability to dynamic analysis of trunk rotation, as the isometric nature of the assessment activity, with the resistance positioned against the shoulders, would have resulted in apparent contributions from muscles not traditionally related to rotation. A clear example of this is identifiable in the significant contribution from the pectoralis major identified in the female subjects. Therefore, Kumar *et al.*'s (2002) study, though providing methodological and kinesiology data, has limited applicability in a dynamic performance setting.

Pope *et al.* (1986) conducted a similar investigation without external resistance in order to compare the torque developed in axial rotation in relation to the activation of the muscles of the trunk. As in Kumar *et al.*'s (2002) research, passive electrode placement was set at intervals of 0.02m over the belly of the muscles. These were applied to the internal oblique, external oblique, rectus abdominus, the sacrospinal muscles and the transversospinal muscles. The subjects completed a series of maximal voluntary contractions (MVC) followed by a series of graded contractions at 25, 50 and 75 % of their pre-recorded MVC's. Pope *et al.* (1986) recorded the highest bilateral asymmetry in the activation level of the erector spinae and external obliques. Similarly to Kumar *et al.* (2002), Pope *et al.* (1986) identified that erector spinae and rectus abdominus activation was related to axial rotations. Statistical analysis exhibited no significant differences between the right and left rectus abdominus and internal obliques, therefore suggesting that their role was stabilising the motion, with the external obliques acting as the prime mover in the production of axial rotations of the trunk.

Previous research investigating axial trunk rotation highlighted a number of pertinent findings that need to be taken into account when analysing kayaking technique. Pope *et al.*'s (1986) identification that the external obliques contribute significantly during the rotation of the trunk and that the rectus abdominus and internal obliques provide assistance, indicates that the measurement of the external oblique activity during paddling is very important. Although the findings only indicate a supporting role from the rectus abdominus, it will still be a muscle for focus. This is due to the design of a kayak hull having little natural stability, therefore the rectus abdominus may be influential in the balancing of the kayak during rotation and the aim of the current research is to determine the role of the trunk and legs in paddling performance. Furthermore the identification of higher levels of flexibility around the spine in female subjects is an interesting area that will require monitoring, as this may affect the degree of rotation, which may have an effect on technique and performance when compared between genders.

When measuring the activation of trunk muscles it is important to take into consideration the electrical signals associated with the contraction of cardiac muscle (Allison, 2003). Allison (2003) identifies that the ECG artefacts in EMG's can cause problems when trying to identify the onset of trunk muscle activation. Bipolar silver-silver chloride passive surface electrodes were placed on the rectus abdominus, external obliques and longissimus sampling at 1000 Hz. Algorithms were produced in an attempt to determine the onset of the muscle activation, these were applied to the RMS EMG traces. Findings indicated that the algorithms were reliable in the identification of the onset of the activation of trunk muscles; however the recommendations for the application of the algorithm would be to help in trial selection from which visual inspection should be employed.

As suggested by Kemecsey (1986) and further demonstrated in chapter 3 (A notational analysis of flatwater sprint kayaking), the legs may be as important to kayaking performance as the trunk, therefore a review of any literature discussing the application of EMG during leg motion may provide further methodological considerations. Matheson *et al.* (2001) investigated the EMG activity in different seated quadriceps exercises, specifically the vastus lateralis, vastus medialis and rectus femoris. Silver-silver chloride passive surface electrodes were positioned over the muscle belly and EMG activity was sampled at 10,000 Hz. A Cybex® 340 isokinetic dynamometer was used as the basis for the quadriceps exercise. Findings indicated that the quadriceps activity levels were higher during only some eccentric exercises rather than all eccentric exercises as previously thought (Matheson *et al.*, 2001). Furthermore Matheson *et al.* (2001) identified significant interaction between the rectus femoris, vastus medials and vastus lateralis during concentric contractions, however this was not found to be the same during eccentric contractions. In addition the findings highlighted that not all exercises created the same levels of activity within the muscle therefore selection of training exercises is important.

In response to Matheson *et al.*'s (2001) findings, the activation of the rectus femoris, vastus medialis and lateralis will be of interest when analysing the leg performance during kayak paddling. This is important as the use of the quadriceps group in the driving of the straightening leg during paddling has been suggested by Kemecsey (1986) to be essential. This is further demonstrated in the findings of research described in chapter 3, in which the international paddlers exhibited a greater level of leg extension than the lower ability paddlers, thus reinforcing Kemecsey's (1986) suggestion that the straightening of the leg is important within performance. Furthermore the contribution from the vastus medialis and lateralis may be important as any imbalance of force production between the muscles could affect the direction of force application onto the kayak causing excess boat motion. This in turn would affect the drag on the kayak hull through the generation of a constantly changing wetted surface area. Finally any imbalance in the muscles could also cause injury problems as an important role of these muscles is to stabilise the knees.

The final application of EMG within kayaking that requires attention is the possibility of utilising EMG as a determinant of muscle force. The prediction of muscle force from EMG activity is an area well researched by many authors (Dowling, 1997; Fiebert *et al.*, 1992; Frazer *et al.*, 1998; Hof, 1984; Lawrence and De Luca, 1983; White and Winter, 1993). Hof (1984) provides an overview of the theory of the relationship between muscle force and activation levels. Hof (1984) explains that

'When studying the mechanism of EMG generation it is quite evident the EMG intensity should increase with the muscle force'

Hof (1984, pp.129)

Under isometric conditions when the force increases slowly (quasi-static) a linear relationship between the two exists, although it is important to note that it is not supported by all research (Perry and Bekey, 1981). During dynamic conditions the relationship is not as simple, three assumptions must be applied for the basic EMG to force processing theory:

1. that it be assumed that the processed EMG is an adequate measure of activation;
2. that the muscle length is determined in some way;
3. and, that the muscle force from these two signals be calculated on the basis of a physiological model of the muscle.

Hof (1984, pp. 131)

Hof (1984) identifies that many different techniques have been employed, all with varying accuracy and validity. It is this reason that a number of researchers have declared that the use of EMG as a tool of determining muscle force is not accurate enough to give valid measures (Hof, 1984; Trew and Everett, 2005). This however has not stopped many researchers attempting to develop systems that produce valid results. White and Winter (1993) attempted to determine the muscle forces produced during gait from the EMG signals and musculotendon kinematics.

Inverse dynamics were utilised in conjunction with the EMG signals, and muscle force and length measures. Findings indicated that the model developed was suitable for the use set out at the start of the investigation, this despite the authors admittance that there were errors within the system, especially inherent errors with the determination of joint moment validity. Therefore the use of EMG as a tool for determining force production will not be employed in the current research thesis. The main use will be to investigate the levels and patterns of activation and will be used in conjunction with the kinematic analysis to further understand the contribution of individual muscles within the paddling technique.

3.3.2. Method

Pilot Testing was completed at Holme Pierrepoint National Water Sports Centre, Nottingham. Two subjects took part in the testing protocol (1 male; 1 female) both members of the BCU performance development squad and each provided informed consent and completed a medical questionnaire. Subjects were prepared for electromyography by marking sites over the belly of the muscles of interest. These were, the central segments of the left and right Rectus Abdominus (LRA, RRA), External Obliques (LEXO, REXO), Rectus Femoris (LRF, RRF), Biceps Femoris (LBF, RBF) and medial head of the Gastrocnemius (LG, RG). These muscles were selected due to the actions resulting from muscular contraction and their potential importance in trunk and leg movement during kayaking (table 3.1). Each site was shaved using disposable Bic razors, after which the site was cleaned with isopropyl alcohol swabs. Medicotest blue sensor adhesive passive surface EMG electrodes were positioned 0.02 m apart in line with the muscle fibres on the prepared sites and connected to an MIE data logger via 4K EMG preamplifiers (3 – 250 Hz) which were attached to the skin with medical adhesive tape. EMG signal quality was assessed using MyoDat (v6.47), if a channel exhibited interference or lack of signal, the muscle site was cleaned and new electrodes were applied. Reference electrodes were positioned on the clavicle and lateral malleolus of the fibula for the trunk and legs respectively.

Table 3.1. Concentric actions of the muscles during analysed during on-water paddling.

Muscle	Action
Rectus Abdominus	Trunk Flexion
External Obliques	Trunk Rotation, Trunk Flexion
Rectus Femoris	Hip Flexion, Knee Extension
Biceps Femoris	Hip Extension, Knee Flexion
Gastrocnemius	Plantarflexion, Knee Flexion (when ankle is in Dorsiflexion)

Once prepared, subjects were asked to complete the testing protocol, consisting of 5 trials over a 90 m distance completed at race speed. The subjects were provided with a 75 m run up to a 5 m calibrated area. Sampling of muscle activity was conducted at 500 Hz during the entire time the subject was on the water, using an MIE data logger. To enable trial identification paddlers were asked to have a stationary moment prior to each trial. The data was then downloaded into MyoDat version 6.47 (MIE Medical Research Ltd.) on an Intel Mobile 2.2 GHz Pentium 4 laptop (Research Machines Plc.). Following visual inspection of the quality of the recorded EMG, data trials were transformed into root mean square EMGs and individual trials were identified and extracted for further analysis.

3.3.3. Exploration of EMG data

Examination of the RMS (Root Mean Square) EMG trace in figure 3.1 of the upper body muscles in conjunction with the torsiometer data highlights some interesting interactions. The selection covers three and a half stroke cycles. This clearly indicates an interaction between the right rectus abdominus and the right external oblique (circled). Furthermore figure 3.1 identifies the asymmetry between left and right paddle strokes, the black and green vertical lines depicting the start and mid point of stroke cycles respectively.

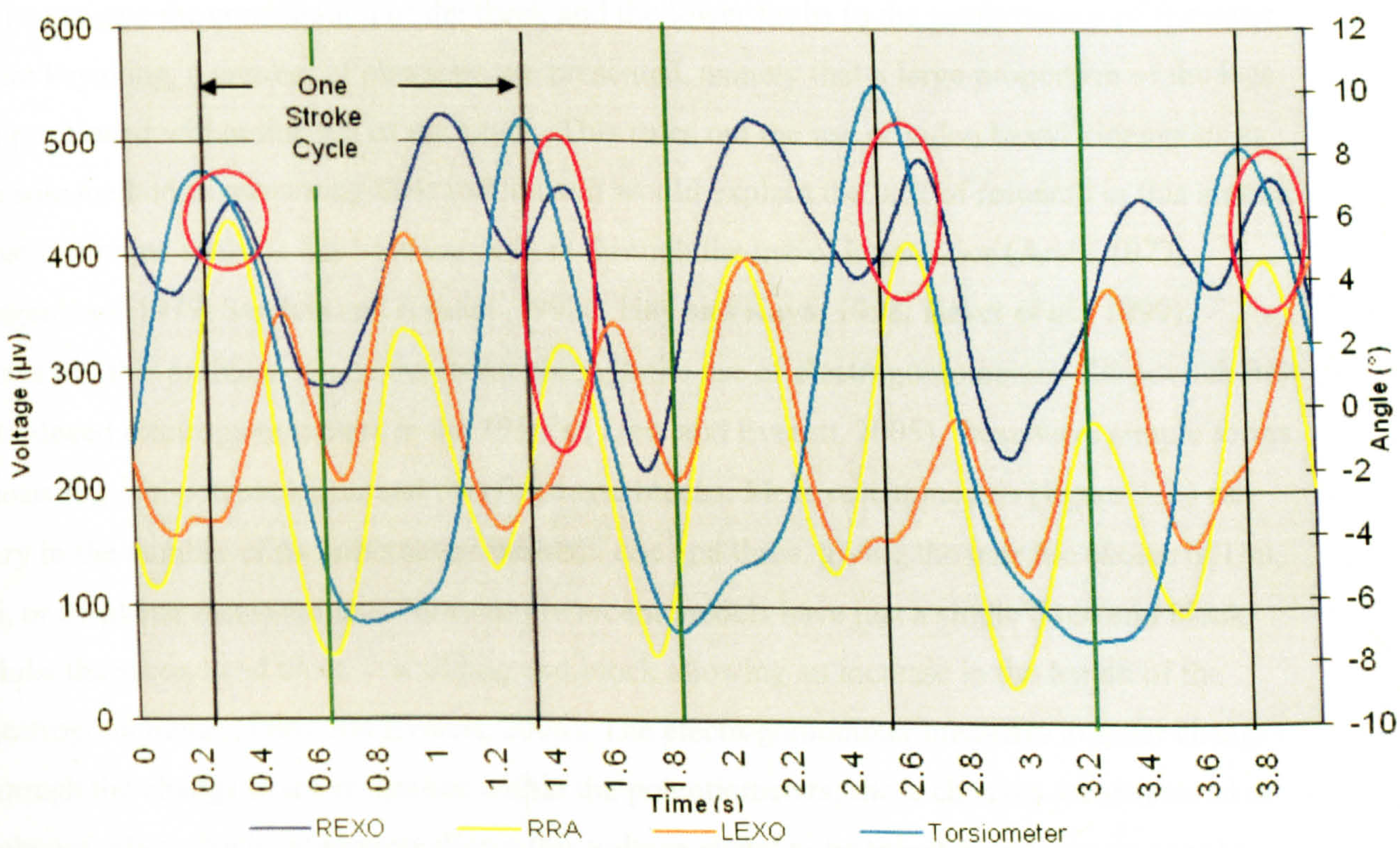


Figure 3.1. Three stroke cycle sample from a maximum effort trial RMS EMG trace.

The asymmetry is clearly evident, in that the mid point (vertical green line) in the stroke cycle does not fall exactly equal distance between the black vertical lines that signify the start and end of the stroke. Furthermore there is an indication of an asymmetry between the activation levels of the left and right external obliques clearly depicted in figure 3.1, the right external oblique exhibiting greater activation throughout the paddling action.

The pilot testing indicated that the MIE Medical Research Limited EMG and data logger system was suitable for use within the water based environment. Generally the recorded raw EMG data were of good quality, however in some of the data sets signal interference was evident. The latter may have occurred due to crosstalk from other muscles in the locality of the electrodes, indicating that the positioning of the electrodes over the muscle belly of interest needed to be optimized to ensure the quality of the recorded EMG data. (for further trials see appendix B).

3.4. Electrogoniometry

3.4.1. Review of technical aspects of electrogoniometry applicability.

To investigate the contribution of the trunk and the lower limbs to the performance of flatwater sprint kayaking, a number of obstacles are presented, namely that a large proportion of the legs are positioned within the hull of the kayak. This rules out the use of video based kinematics as the sole method of measuring their motion and would explain the lack of research in this area as most technique analysis has been carried out through the use of kinematics (Ariel, 1977; Plagenhoef, 1979; Sanders and Kendal, 1992a; Hay and Kaya, 1998; Baker *et al.*, 1999). However, this problem can be overcome through the use of electrogoniometers. Karpovitch first introduced electrogoniometers in the 1950's (Trew and Everett, 2005), these were simple forms consisting of a potentiometer and two fixed end blocks. More recent models (figure 3.2.) can vary in the number of potentiometers between one and three, giving the user the choice of Uni, Bi, or tri-planar measurement. Furthermore recent models have just a single fixed end block, whilst the second end block is a sliding end block allowing an increase in the length of the electrogoniometer (Trew and Everett, 2005). The electrogoniometer measures angular changes through the change in the resistance within the potentiometers; these changes are measured as voltages, after which calibration allows this voltage signal to be transformed into an angular displacement (Trew and Everett, 2005).

Electrogoniometer design is such that only small forces are required to bring about change in the resistance of the potentiometers, therefore, resulting in very sensitive readings. It is therefore paramount that the attachment of the electrogoniometer is exact to ensure valid and reliable readings. Another important factor due to the sensitive nature of electrogoniometers is the assessment of the accuracy and reliability of the electrogoniometer (Shiratsu and Coury, 2003). Shiratsu and Coury (2003) focused on the accuracy and reliability of the Biometrics XM180B, XM150B I and II electrogoniometers; and the Z110 and Z180 single axis torsiometers. A specific gauging device was designed for this exact purpose, which was calibrated using an electronic precise milling machine for recording the linear displacements.

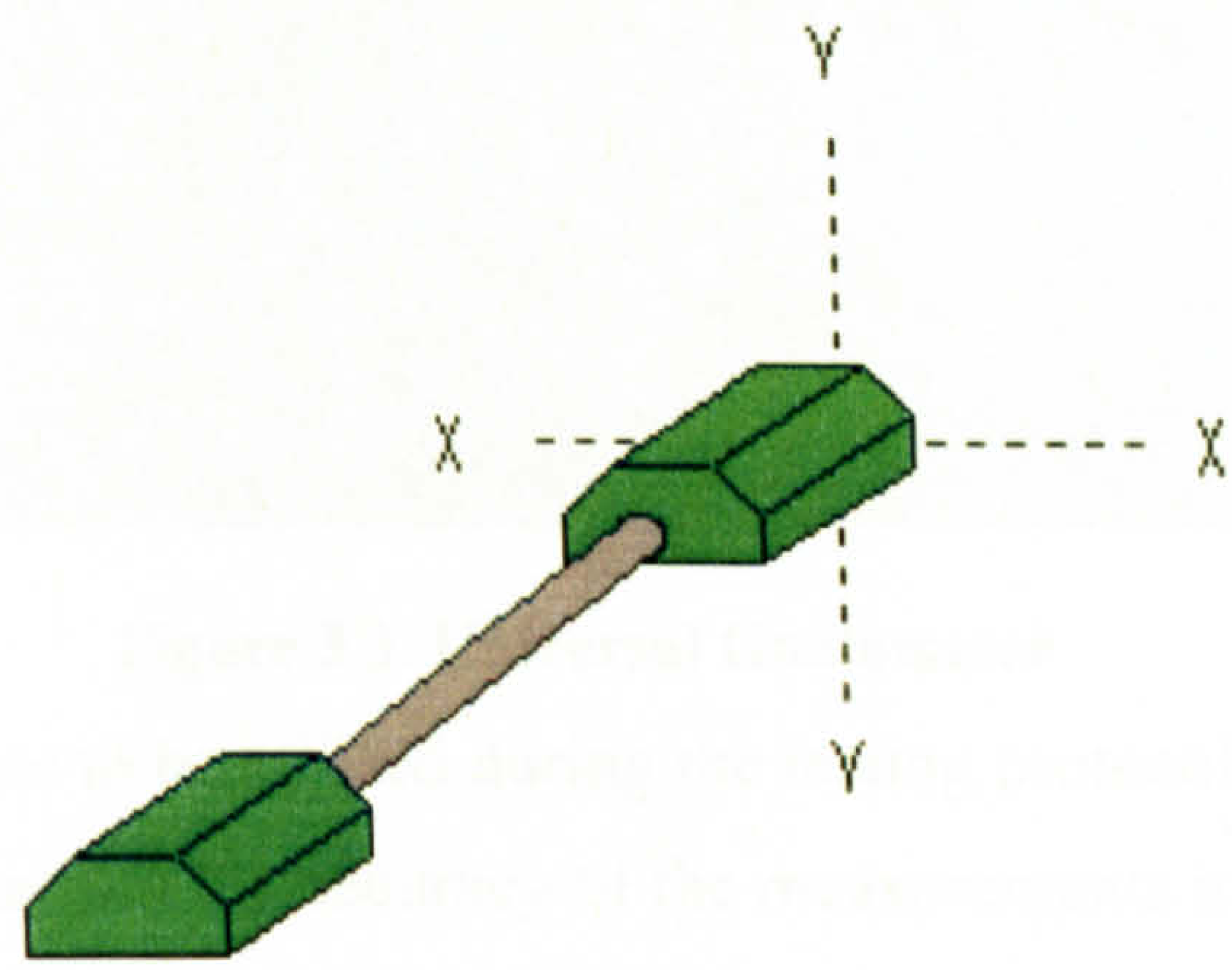


Figure 3.2. Schematic of Biometrics SG150/W Bi-planar Electrogoniometer.

Each electrogoniometer was tested 5 times. Prior to each test the electrogoniometer was re-attached to the calibration device to ensure impartiality. The electrogoniometers were tested through a 1° incremental test. Results indicated that maximum errors presented by the electrogoniometers were below ±3°, an error accepted by the manufacturers. However Shiratsu and Coury (2003) additionally found that the torsiometers did not stay within this accepted limit, instead there was a 7° error for the right rotation and a 5° error for the left rotation. Furthermore Shiratsu and Coury (2003) indicated that the electrogoniometers did not exhibit identical error patterns, therefore advising that any use of Biometrics XM150B I and II electrogoniometers, and Z110 and Z180 single axis torsiometers should only be undertaken after all electrogoniometers and torsiometers have been calibrated separately.

3.4.2. Method

3.4.2.1. Electrogoniometer Accuracy Assessment

Prior to the on water pilot testing the accuracy of the bi-planar Biometrics XM150B waterproof sliding electrogoniometers required assessment, in accordance with Shiratsu and Coury (2003) recommendations. This was carried out using a universal plastic goniometer (see figure 3.3).

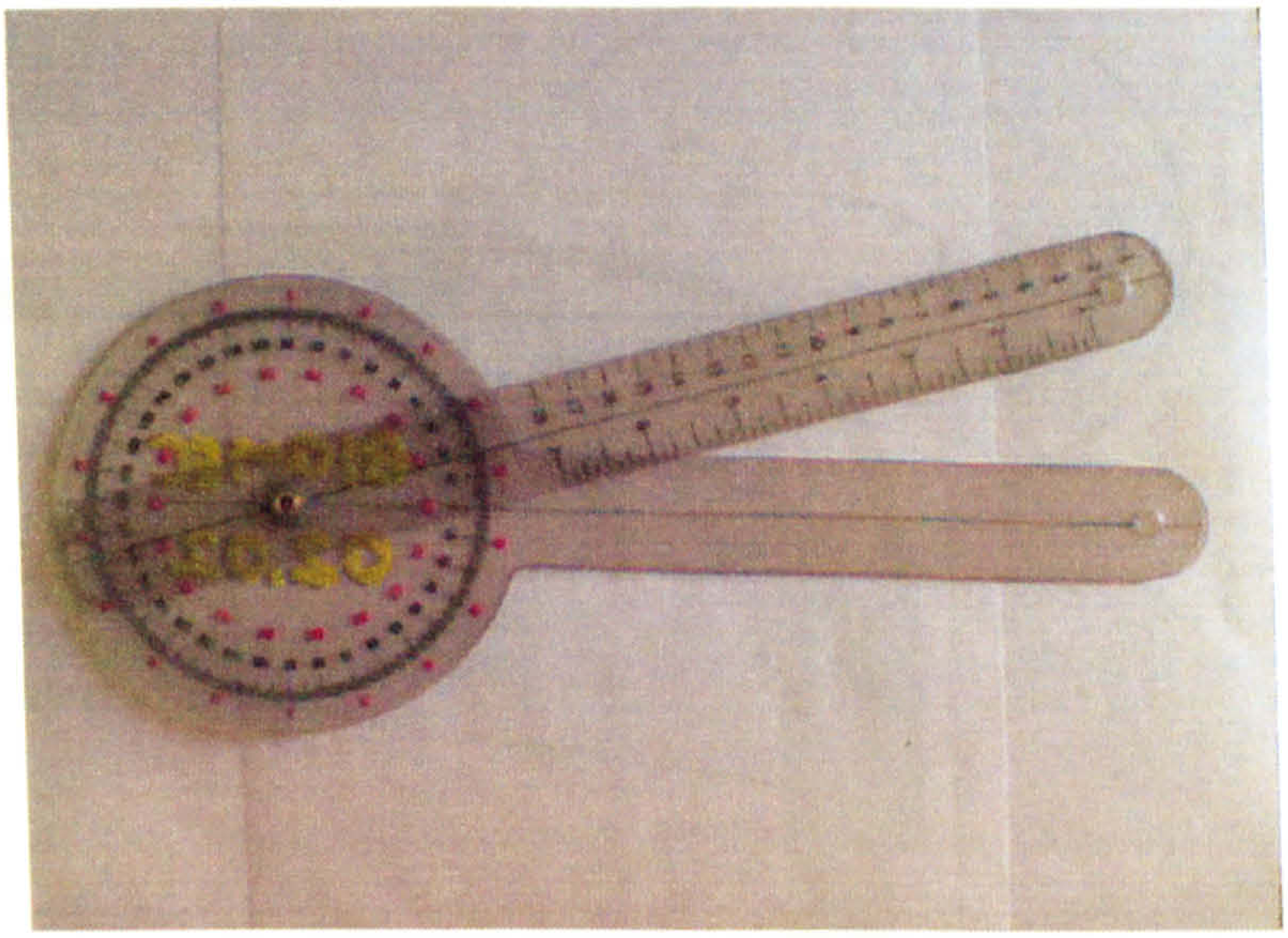


Figure 3.3. Universal Goniometer

Four electrogomioneters were to be utilised during the testing protocol, therefore all required individual assessment to establish the accuracy of the measurements in the X-plane and Y-plane. To assess X-plane measurement the electrogoniometers were fixed in a central position of each of the protruding plastic arms, with a small wedge under the moving end block to keep the electrogoniometer level. Furthermore the centre of the universal goniometer was positioned at the midway point between the two end blocks (see figure 3.4).

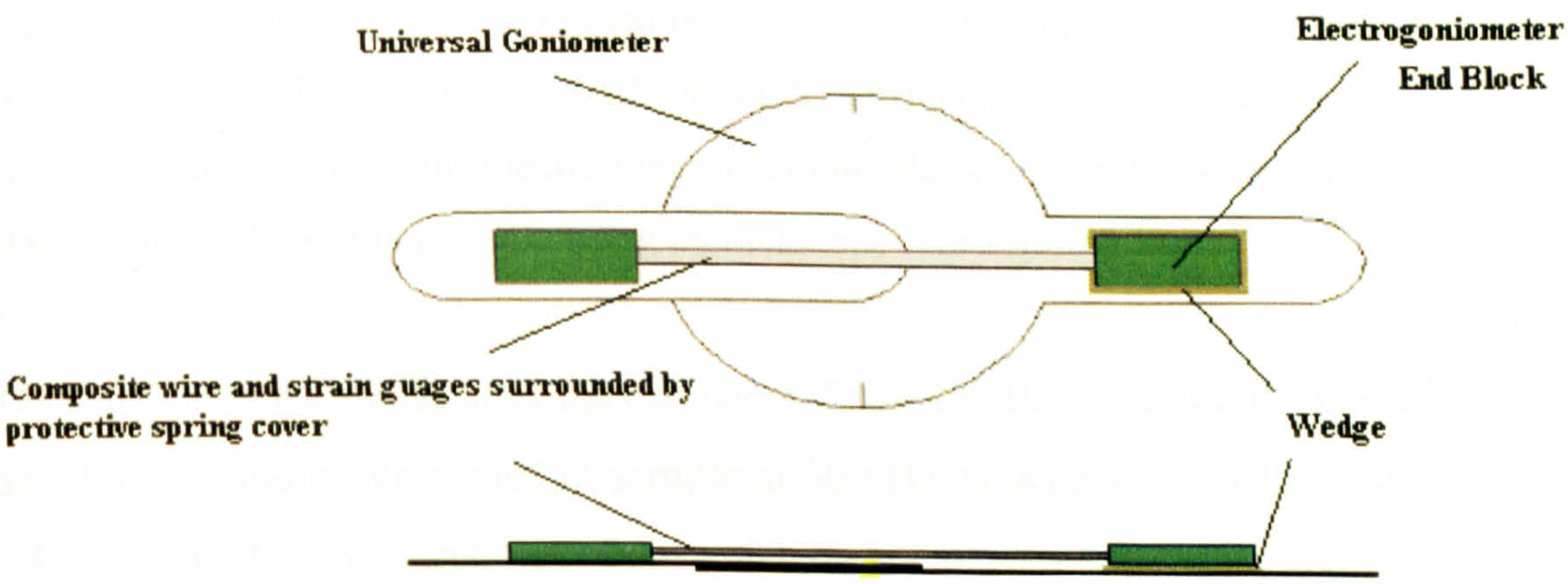


Figure 3.4. Attachment of Electrogoniometer to Universal Goniometer for accuracy assessment in the X-Plane

The goniometer was then positioned at zero (as seen in figure 3.4) and moved through increments of 5° to 90° clockwise and was then repeated anti-clockwise, with each position being held for 4 seconds before being returning the goniometer to zero and then to the next 5° increment. This was repeated 3 times for negative and positive directions.

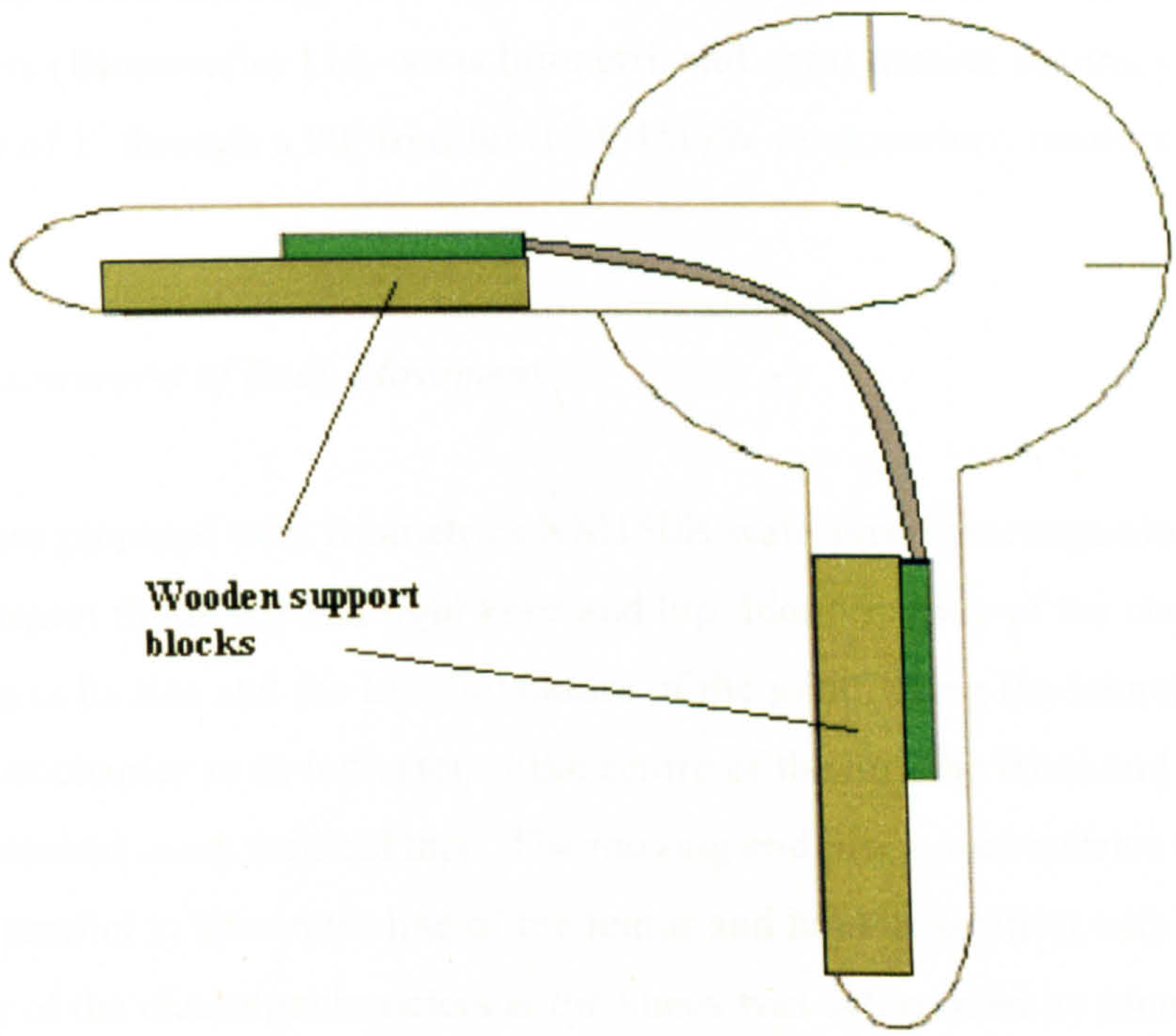


Figure 3.5. Schematic of the fixation of the Electrogoniometer to the universal goniometer for the accuracy assessment in the Y-axis

The accuracy assessment of the Y-plane measures was completed using the same protocol as the X-plane, though the attachment method required a small variance. The end blocks were attached to small wooden blocks (0.05 m x 0.015 m x 0.015 m) using medical tape. These blocks were then positioned to ensure the electrogoniometer end block was in the centre of the protruding plastic arms and fixed in position using medical tape (see figure 3.5).

The signal from the sliding electrogoniometers (DC – 250 Hz), adapted for use with the MIE data loggers and programmed to sample at 500 Hz, was down loaded into MyoDat version 6.47 (MIE Medical Research Ltd.) from which the traces were exported into Microsoft Excel for further analysis. The electrogoniometer traces were then plotted against the expected values from the universal goniometer.

Although Shiratsu and Coury (2003) raised questions concerning the first generation of Biometrics Ltd toriosmeters (Z110 and Z180) this has not been the case with the current generation (Q110 and Q150). The torsiometers to be employed in the current research were the Biometrics Q150/W waterproof torsiometers. These torsiometers have previously been utilised by Lu *et al.* (2007) and Jones and Kumar (2007), neither of whom identified any inaccuracies within the measurements, therefore assessment of accuracy was deemed unnecessary unlike the

Biometrics XM150B electrogoniometers. Furthermore guidelines presented by the manufacturers (Biometerics Ltd, www.biometricsltd.com) outline accuracy limits of ± 2° and repeatability of 1° through a 90° trial for the Q150/W torsiometers, reinforcing the accuracy of the sensors.

3.4.2.2. Measurement of Body Movement.

Subjects were prepared with Biometrics XM150B waterproof electrogoniometers positioned on the lateral aspect of the left and right knee and hip. Identification of the centre of the hip joint is difficult due to its size and the tri-axial nature of the joint. Using the lateral aspect of the head of the greater trochanter as an indicator of the centre of the hip, the fixed end positioned superior to the joint, attached using medical tape. The moving end block was inferior to the greater trochanter parallel to the centre line of the femur and held in position with medical tape. Positioning of the electrogoniometers at the knees was determined by identification of the lateral distal condyle of the femur and the lateral proximal condyle of the tibia. The centre of the knee was ascertained to be the point mid way between the centre of these reference points. The fixed end of the electrogoniometer was positioned superior to the knee joint on the lateral aspect of the thigh parallel to the centre line of the femur, held in position with medical tape, with the moving end block inferior to the knee on the lateral aspect of the shank parallel to the tibia secured in position with medical tape.

In addition to the electrogoniometers, a Biometrics Q150/W torsiometer was employed to measure trunk rotation. The torsiometer was positioned over the spinaeous processes of the 5th lumbar and 7th thoracic vertebrae. An initial base line was taken to start with the subjects positioned in a comfortable position in the cockpit of the kayak with the feet on the foot plate, while the spine was in a vertical position. During this baseline both paddlers had their knees flexed providing a start or zero position from which extension and flexion of the knee can be assessed.

The subjects then completed the testing protocol with data being recorded and stored on the MIE data logger at 500 Hz. The data was down loaded into MyoDat v6.47 analysis software from which individual trials were exported into Microsoft Excel XP for further analysis. The data was then smoothed using a 200 ms moving average, allowing a clearer indication of what was happening at the individual joints.

3.4.3. Exploration of Electrogoniometer Data

3.4.3.1. Accuracy

The accuracy assessment identified a number of findings. Initially findings exhibited that there is clear inconsistency in the accuracy across all four electrogoniometers. However, all Biometrics XM150B electrogoniometers displayed a general trend, measuring lower than the actual angle in the X-plane and higher than the angle in the Y-plane (table 3.2). Findings for the mean error identified that electrogoniometer 1 displayed the lowest levels of error in both planes and positive and negative corrections all of which under 1°. Electrogoniometer 3 displayed mean errors of less than 1° in three of the four measures with only the mean error in the positive X-plane displaying a mean error of -1.53 ± 0.61. Electrogoniometers 2 and 4 generally displayed larger mean errors across all measures than electrogoniometers 1 and 3.

Table 3.2. Mean error and range identified in individual electrogoniometers.

Electrogoniometer Number	X Plane Mean Positive Error (°)	X Plane Mean Negative Error (°)	Y Plane Mean Positive Error (°)	Y Plane Mean Negative Error (°)
	(range)		*(range)*	
1	-0.81 ± 0.74	0.71 ± 0.37	-0.74 ± 1.75	0.24 ± 0.34
	(3.5)		*(3.0)*	
2	-2.28 ± 0.09	2.48 ± 0.14	-0.88 ± 1.71	1.12 ± 0.42
	(11.3)		*(6.1)*	
3	-1.53 ± 0.61	0.72 ± 0.55	-0.94 ± 0.47	0.39 ± 0.13
	(7.2)		*(3.4)*	
4	-3.11 ± 0.14	3.57 ± 0.23	-2.35 ± 0.61	1.23 ± 0.35
	(14.3)		*(8.5)*	

Investigation of the ranges of error corroborated the findings of the mean error, identifying smaller range in electrogoniometers 1 and 3 than electrogoniometers 2 and 4. Overall maximum ranges of error varied between 3° and 14.3° (table 3.2). Only electrogoniometer 1 fell within the accuracies of ± 2° claimed by the manufacturer in both the X and Y-planes, with electrgoniometer three coinciding with the proposed accuracy levels in the Y-plane.

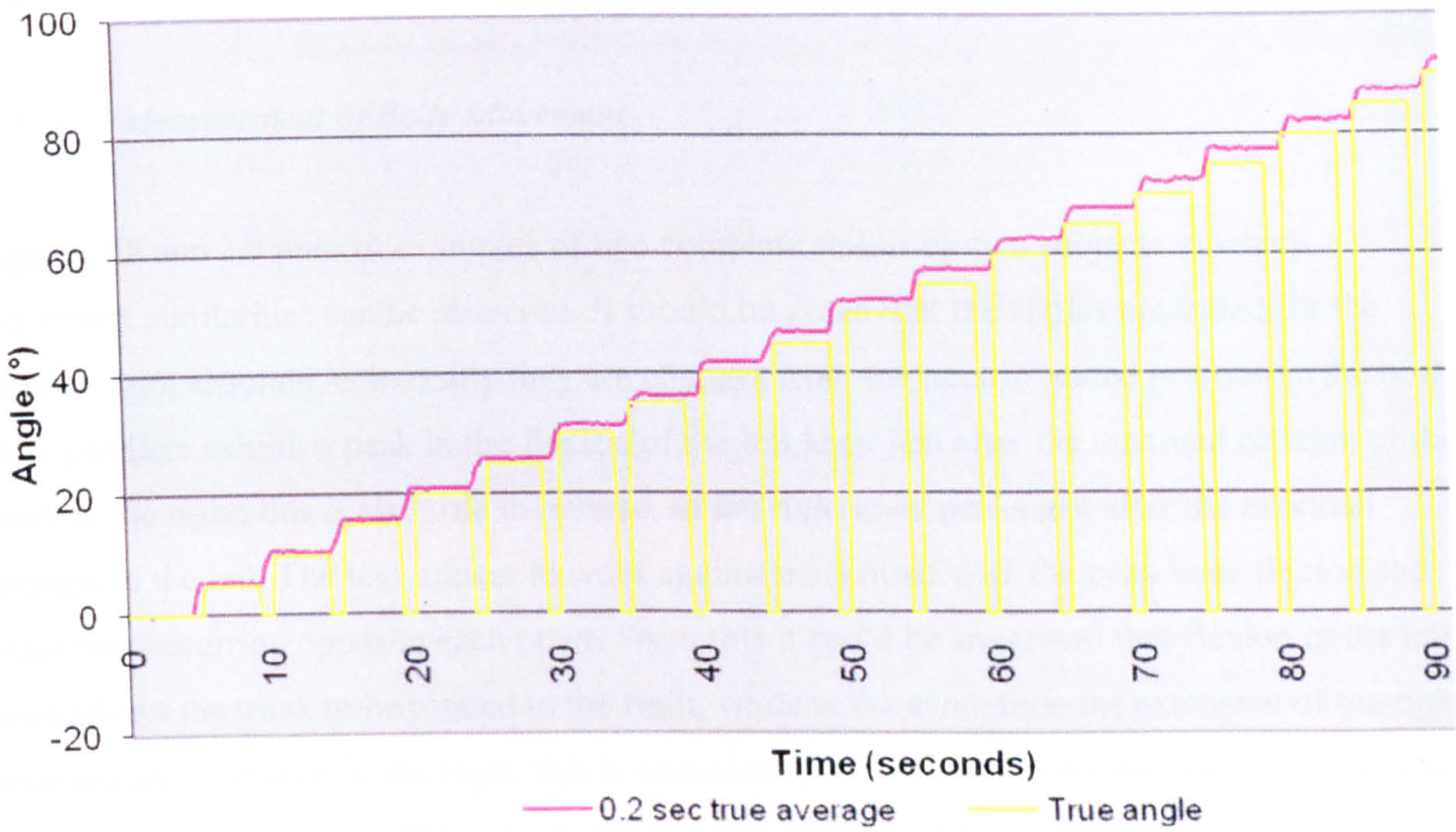


Figure 3.6. Example of trace comparison between expected and recorded signal during the positive angles in the X plane for electrogoniometer 1 .

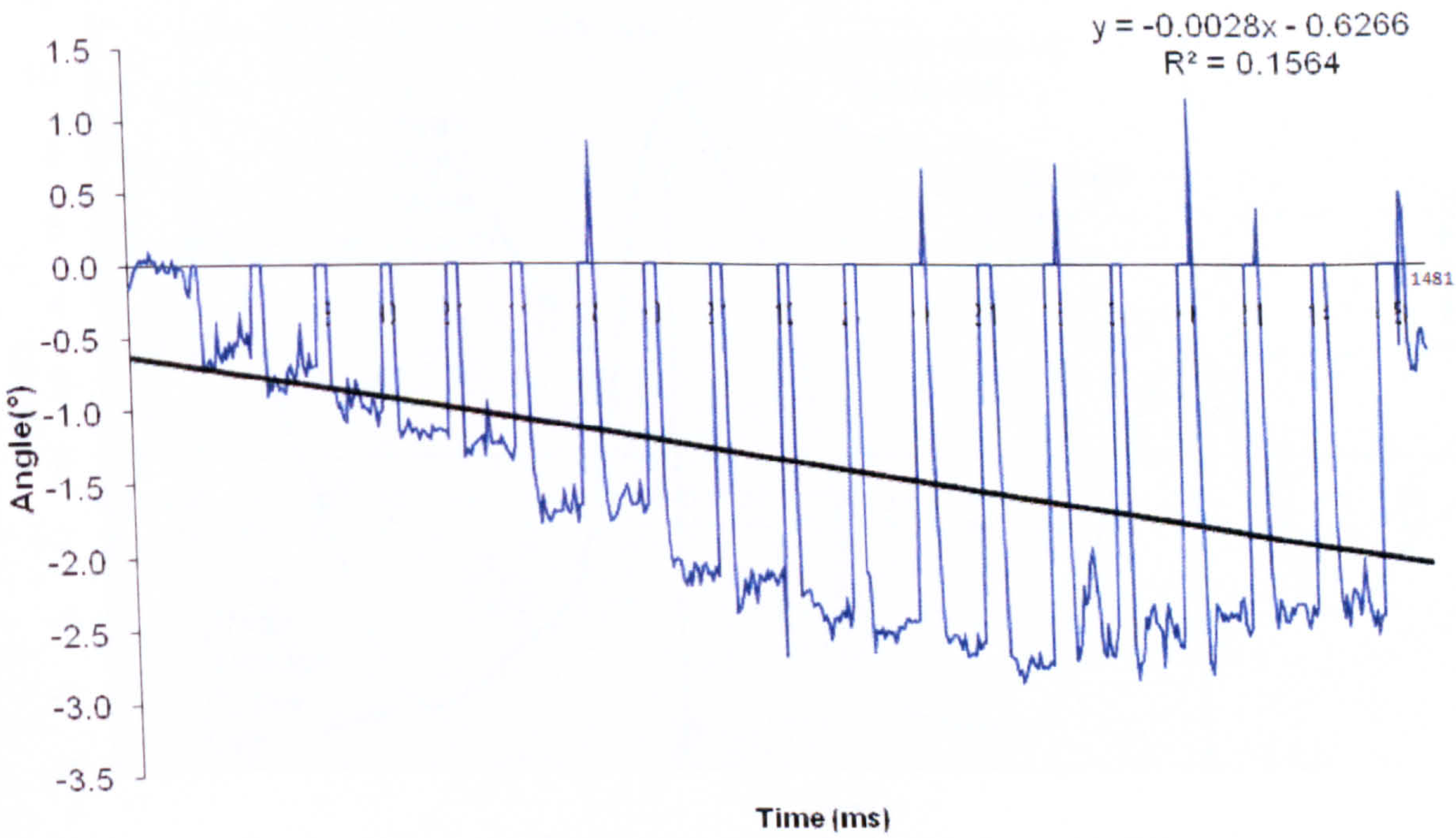


Figure 3.7. Example of error in measurement during the positive angles in the X-plane for electrogoniometer 1.

An example of an accuracy assessment trace (figure 3.6) provides a clear indication of general trend that emerged across the majority of trials. This trend was characterised by an increase in the measurement error as the angle increased, further evidence of which can be found in appendix C. Furthermore this is clearly depicted in figure 3.7 by the trend line applied to the data, illustrating that as the measured angle increases so does the error in the measurement.

3. 4. 3. 2. Measurement of Body Movement

Figures 3.8 and 3.9 present examples of two complete stokes by two subjects in which movement similarities can be observed. It should be noted that the angles presented for the knees are not absolute, conversely they are changes from the neutral seated position in the boat. Both paddlers exhibit a peak in the flexion of the left knee just after the maximal rotation of the trunk to the right; this is also true in reverse, as the right knee peaks just after the maximal rotation to the left. The legs appear to work against each other with the peak knee flexion and extension occurring opposite each other. From this it could be suggested that flexion of the left knee allows the trunk to be rotated to the right, while at the same time the extension of the right knee assists in rotation to the right, this is also seen in reverse. This corroborates the technique presented by Kemecsey (1986) who indicated an extension of the contralateral knee should coincide with the rotation characterised by a backward movement of the contralateral shoulder.

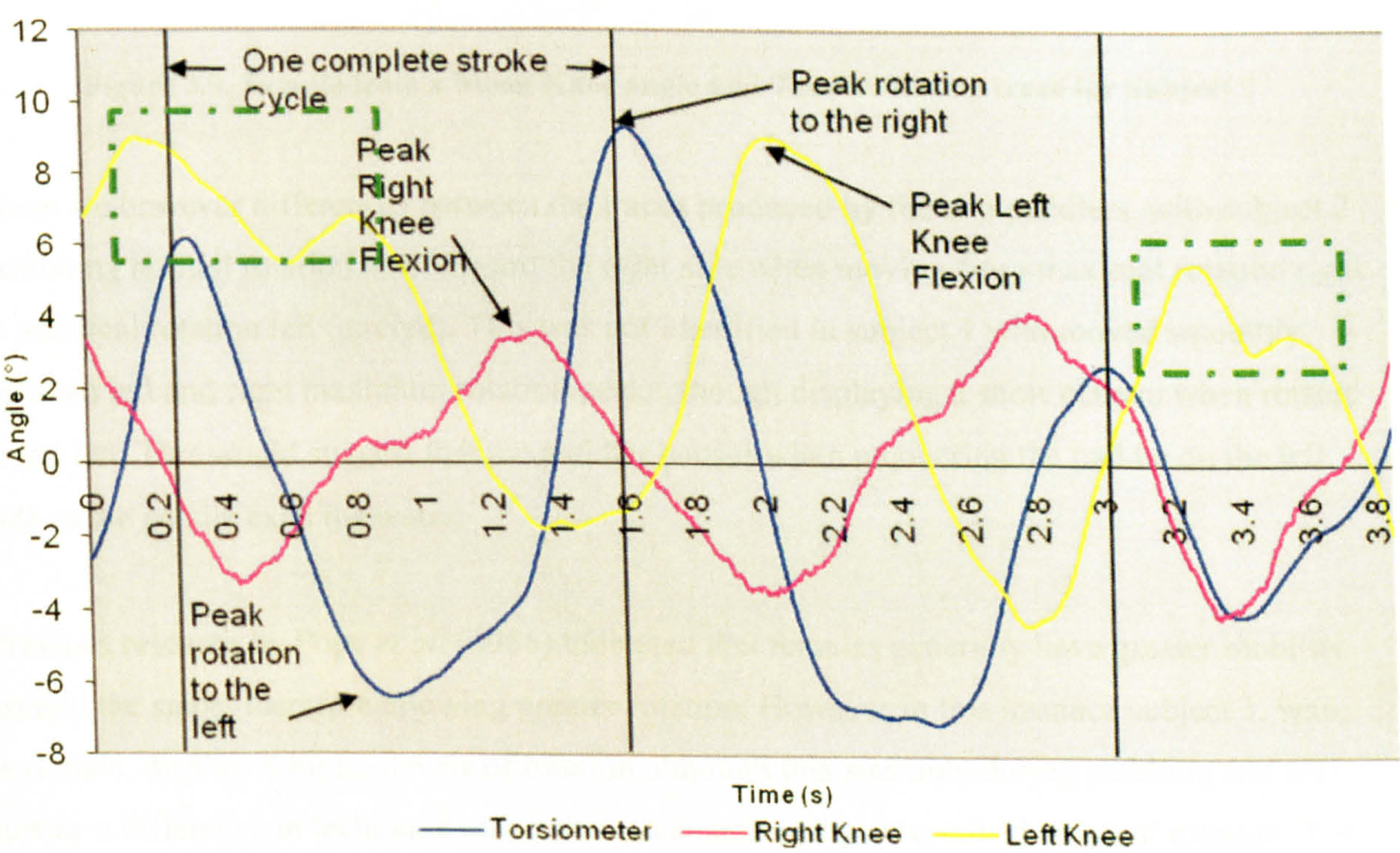


Figure 3.8. A sample from a Mean knee angles and trunk rotations trace for Subject 1

Further similarities are visible in the left knee of both paddlers (depicted by the green dashed boxes), characterised by a short extension at the knee after peak followed by a secondary flexion. This secondary flexion appears to generally occur with and just after peak rotation to the contralateral side. This may be directly linked with the exit of the blade on the contralateral side as the peak rotation occurs simultaneously with the paddle exit.

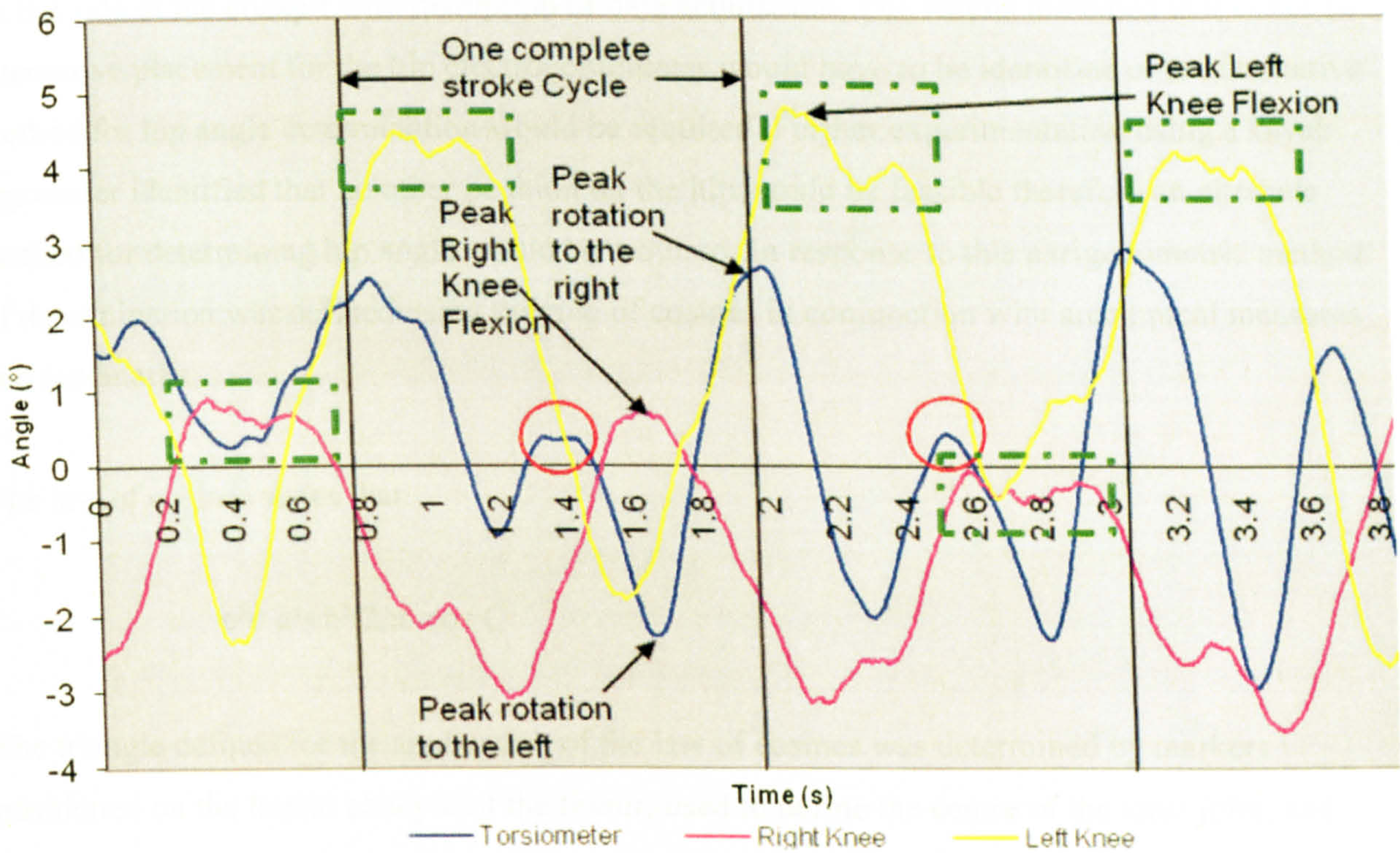


Figure 3.9. Sample from a Mean Knee angle and Trunk rotation trace for Subject 2

There are however differences between the traces produced by the two paddlers, with subject 2 exhibiting a small rotation back toward the right side when moving from maximal rotation right to maximal rotation left (circled). This was not identified in subject 1 who moved smoothly between left and right maximum rotation peaks, though displaying a short plateau when rotated to the left. This would suggest that the paddler pauses when recovering the paddle on the left side as the paddle exits the water.

Previous research by Pope *et al.* (1986) indicated that females generally have greater mobility around the spine, therefore allowing greater rotation. However in this instance subject 1, who was male, displayed higher levels of rotation although this was only during paddling and may just be a difference in technique rather than an anatomically determined range of rotation. The preliminary findings derived from the traces of the trunk and knees has identified that feasibility of the application of torsiometers and electrogoniometers for monitoring and assessing the actions of the trunk and legs. Application of these devices during this pilot study provided empirical evidence for the importance of the trunk and legs during sprint kayak paddling technique.

The pilot testing demonstrated a number of limitations; some expected others unforeseen within the protocol. The position of the electrogoniometer on the lateral aspect of the hip was not feasible due to the kayak cockpit being too narrow, resulting in the electrogoniometers knocking on the side of the cockpit with disruption of data acquisition. The results indicated that either an alternative placement for the hip electrogoniometer would have to be identified or an alternative method for hip angle determination would be required. Further experimentation using a kayak ergometer identified that no other position on the hip would be feasible therefore an alternate method for determining hip angle would be required. In response to this a trigonometric method of determination was defined using the rule of cosines in conjunction with anatomical measures and landmarks.

The law of cosines states that:

$$c^2 = a^2 + b^2 - 2ab \cos C$$

The triangle defined for the application of the law of cosines was determined by markers positioned on the lateral condyle of the femur, used to define the centre of the knee joint, and positioned 0.25 m vertically above the centre of the hip joint (measure in the anatomical position), identified through the location of the greater trochanter, and the centre of the hip identified as previous.

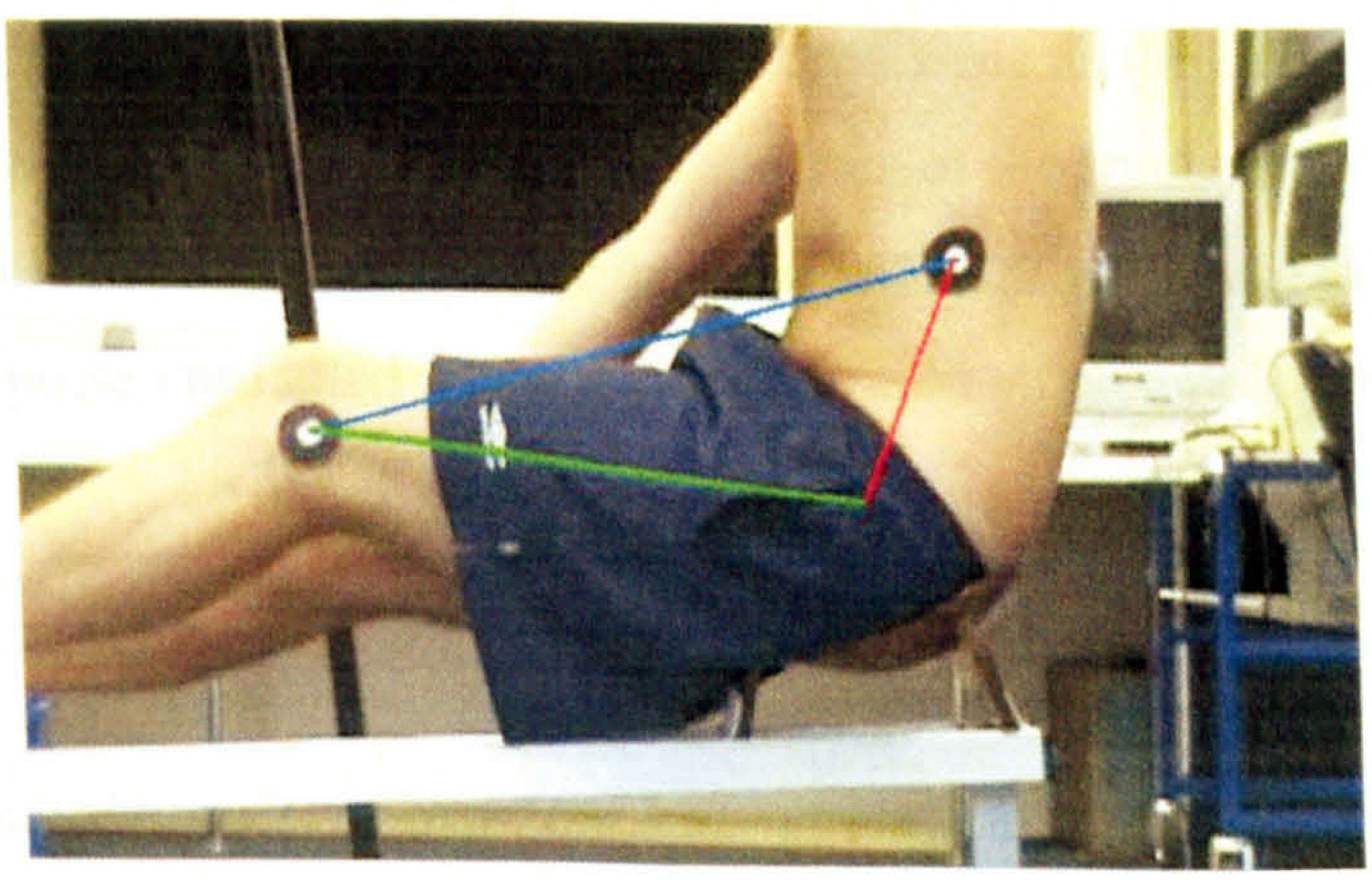


Figure 3.10. Marker set for hip angle determination.

The length of the femur (a - Green) was measured from the head of the greater trochanter to the lateral condyle at the knee. The second side was set at a standard 0.25 m measured vertically from the greater trochancter (b - Red) and the position marked (this position was digitised as the lateral trunk marker). The final side of the triangle was measured using the kinematic analysis, which measured the distance between the lateral trunk marker and the lateral condyle of the femur at the knee (c - Blue).

Another factor that required to addressed was the positioning of the torsiometer, following input from the British Canoe Union (BCU) physiotherapist. The point at which the paddler rotates through the spine is dependent on the position in which they hold their trunk. Paddlers with an upright trunk position will rotate at a lower point in the vertebral column, around the lumbar vertebrae. However paddlers with a hunched position will rotate at a high point, possibly in the thoracic vertebrae, therefore if the torsiometer is positioned too low the rotations of the trunk will not be measured accurately. This therefore would require either the input of the BCU physiotherapist at the final testing to ensure the correct positioning of the torsiometer in relation to the technique adopted by the individual paddler or for two torsiometers to be applied to the subject, one over the lumbar and lower thoracic and one over the middle and upper thoracic vertebrae. It was decided that the use of two electrotorsiometers would be employed, positioning one from the first thoracic (T1) to the tenth thoracic vertebrae (T10) and a second positioned over the eleventh thoracic vertebrae (T11) to the fifth Lumbar (L5) vertebrae. Thus solving the issue of individualised positioning for each subject and allowing comparison across all subjects. Moreover this could provide data on the interaction of the upper and lower trunk during paddling, helping to identify where, if anywhere, paddlers rotate during performance.

The final factor that was identified from both the electrogoniometer and EMG analysis was the issue of synchronising multiple data loggers. This was an issue as the data loggers were limited to 8 channels, therefore to complete an extensive analysis of the trunk and lower leg activity two data loggers are required. This was overcome by the use of a pulse signal module which through the use of an infrared pulse implanted a signal that saturated all channels simultaneously.

3.5. Kinematics

3.5.1. Review of technical aspects of kayaking kinematics.

Kinematic analysis has been employed as the predominant research tool in sprint kayaking, with many researchers using kinematics to quantify technique and performance within sprint kayaking (Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980; Sanders and Kendal, 1992a; Kerwin *et al.*, 1992; Sanders and Baker, 1998; Baker *et al.*, 1999). However, much research has had accuracy and reliability issues due to the nature of the event and technique employed. The major issue is the multi-plannar, multi-axial paddling technique which can only be fully analysed and understood through a comprehensive three dimensional analysis. Previous studies have used the kayak as a calibration tool for the quantification of distances and velocities (Sanders and Kendal, 1992a), others have used reference markers in the field of view (Kerwin *et al.*, 1992) however neither methodology would allow a three dimensional analysis of technique. The major problem is the calibration of the area in which the action will be taking place, more specifically the middle of a regatta lake. The use of reference markers is not suitable as they need to be placed in the plane of motion and any markers placed on water will be open to the flow of the water current or wind. Another problem with sprint kayaking is the size of the area over which the events take place, the shortest of which is 200 m.

In an attempt to overcome this researchers have tried a number of solutions. Hay and Kaya (1998) used a fixed camera on a motor boat that ran parallel to the subject in their kayak, this however will not allow a three dimensional analysis to be carried out. Others have used fixed cameras (Kerwin *et al.*, 1992; Baker *et al.*, 1999; Ong *et al.* 2006) limiting the area over which the data collection may take place. Therefore only a small number of strokes were recorded, but a three dimensional analysis could be undertaken to allow a more encompassing analysis of technique. Baker *et al.* (1999) and Ong *et al.* (2006) both employed fixed camera positions in conjunction with the use of calibration frames 6m long and 2m in height and width.

The technique to be employed within the current research thesis will use fixed camera positions, similar to Baker *et al.* (1999) and Ong *et al.* (2006). This will result in a reduced number of strokes captured however when utilised in conjunction with a floating calibration frame, (figure 4.11) will allow a three dimensional analysis of the upper body to be produced. Combining the three dimensional reconstruction from the kinematic analysis with electromyographic, kinetic and torsiometric measurement techniques will provide an understanding of the motions and interactions of the upper and lower body during the paddling stroke.

Angulo and Dapena (1992) investigated the accuracy of film and video when using them in a three dimensional reconstruction within a large (8 m) field of view. Angulo and Dapena (1992) used a spherical shaped calibration frame 2.4 m in diameter consisting of 68 calibration points. Accuracy checks were carried out both within the calibrated space and using points of known position outside of the calibrated volume. Angulo and Dapena (1992) indicated errors of 7 mm in the X plane, 5 mm in the Y plane and 4 mm in the Z plane with a resultant of 10 mm; this equated to a 0.3% error of the entire space within the calibrated volume. However the extrapolation error exhibited much higher errors; 23 mm in the X plane and 24 mm in the Y plane, with a resultant error of 39 mm or 1.3% of the total space. This therefore highlights the importance that the action must take place within the calibrated volume. The calibration frame used by Angulo and Dapena (1992) was small for the 8 m field of view that was of interest, this may have been a direct cause of the errors found in the accuracy of digitisation as a larger calibration frame would have provided a greater volume in which better accuracy would have been achieved.

Figure 3.11. Floating Calibration Frame.

3.5.2. Method

The floating calibration frame used for the pilot study was a 31 point frame 5 m in length, 2.5 m in width and 1.8 m high (figures 3.11 and 3.12). The frame consisted of a wooden and plastic tube base held in position with guide wires ensuring the base of the frame floated level.

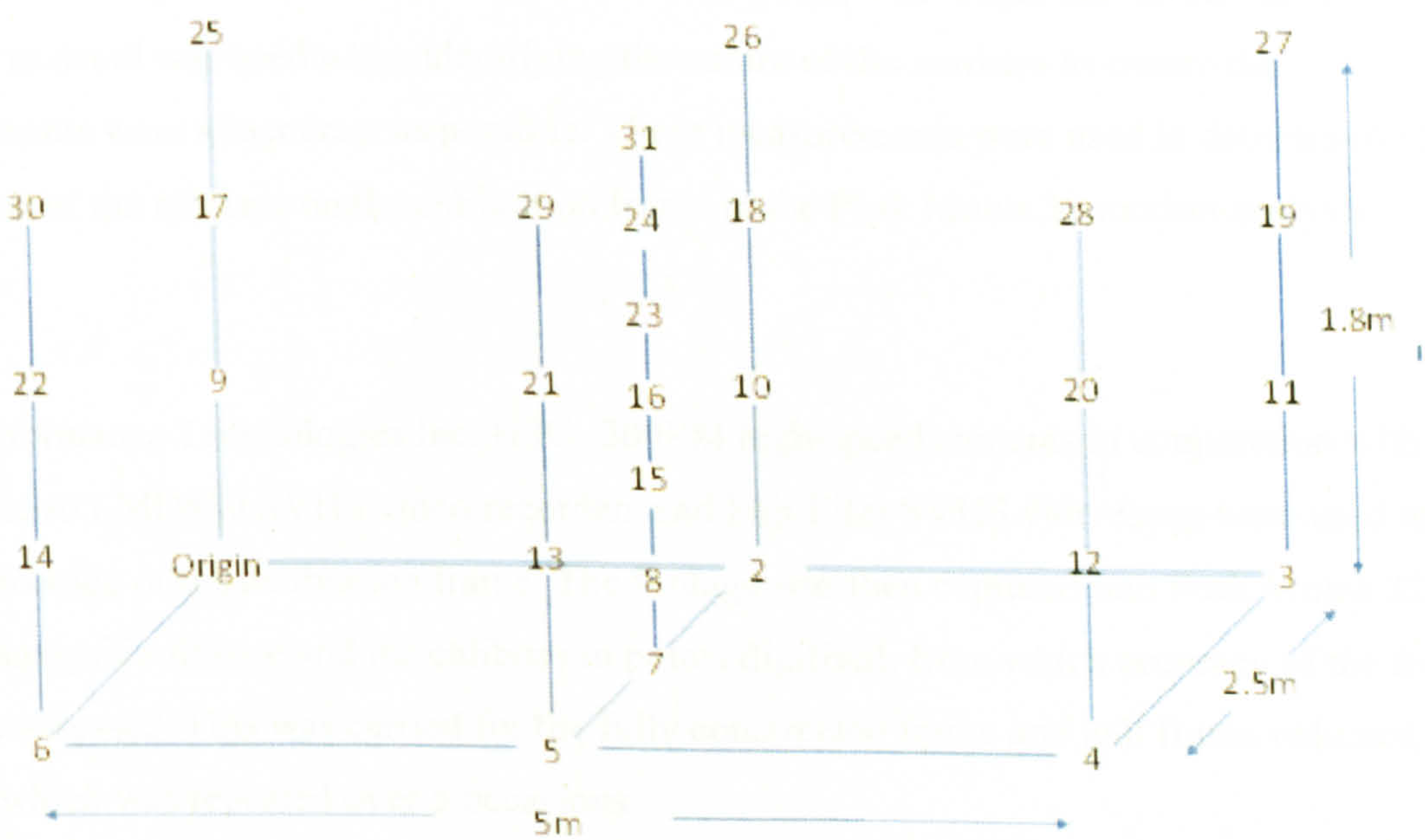


Figure 3.12. Schematic of the Floating Calibration Frame

From this 7 aluminium poles protrude vertically with the outer 6 poles marked vertically at 0.6 m intervals with strips of tape, a single stripe of reflective tape flanked by two stripes of black electrical tape (figure 3.13). The centre pole was marked with the same markers as the outer poles but at smaller intervals of 0.3 m.

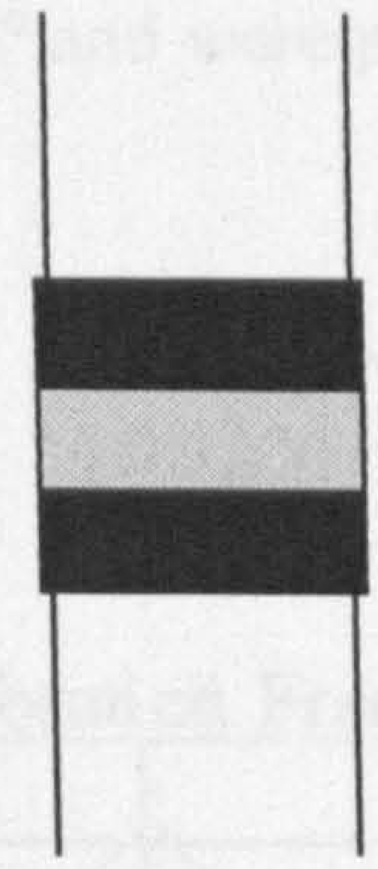


Figure 3.13. Schematic of Markers on the vertical poles of the calibration frame.

To assess the accuracy of the calibration frame a number of tests were required. Initial assessment of the calibration frame accuracy was undertaken on land at the University of Chichester. An origin marker was selected at the base of the frame as this point would have been least affected by wind or water currents, from which string and a tape measure was used to determine the exact distance between the centre of the markers (see appendix E). String was used as it was simpler to ensure the line between the points was taught and direct. Great attention to detail was used when identifying the centre of the markers to ensure the measurements were as accurate as possible. These measurements were used in determining the orientation of the markers on the calibration frame in the Peak Motus 32 motion analysis software.

Peak Performance Technologies Inc. HSC- 200PM high-speed cameras in conjunction with Panasonic AG-MD830 SVHS video recorders and Fuji-Film SVHS videotapes were used to capture footage of the calibration frame. The footage was then captured into Peak Motus 32 motion analysis software and the calibration points digitised, from which accuracy of the frame could be assessed. This was carried for the fully constructed frame and half frame volumes, each of which was repeated over 5 occasions.

On-water testing was undertaken to rectify the limitations previously identified and to determine the accuracy of the calibration frame. The vertical protruding rods that had markers (figure 3.11) positioned along their length had the exposed metal covered in non-reflective masking tape.

This served 2 key purposes; ensuring there would be no glare from the exposed metal in high light conditions and furthermore the white poles provided excellent contrast to the black markers and dark background surrounding the lake. The testing was carried out at Chichester Water Sports Centre, West Sussex. The calibration frame was secured in position with guide ropes staked into the bank and was further supported by a researcher. Camera positions were set with an angle between optical axes of 100° and were positioned at 1.5 m above the surface of the water (figure 3.14).

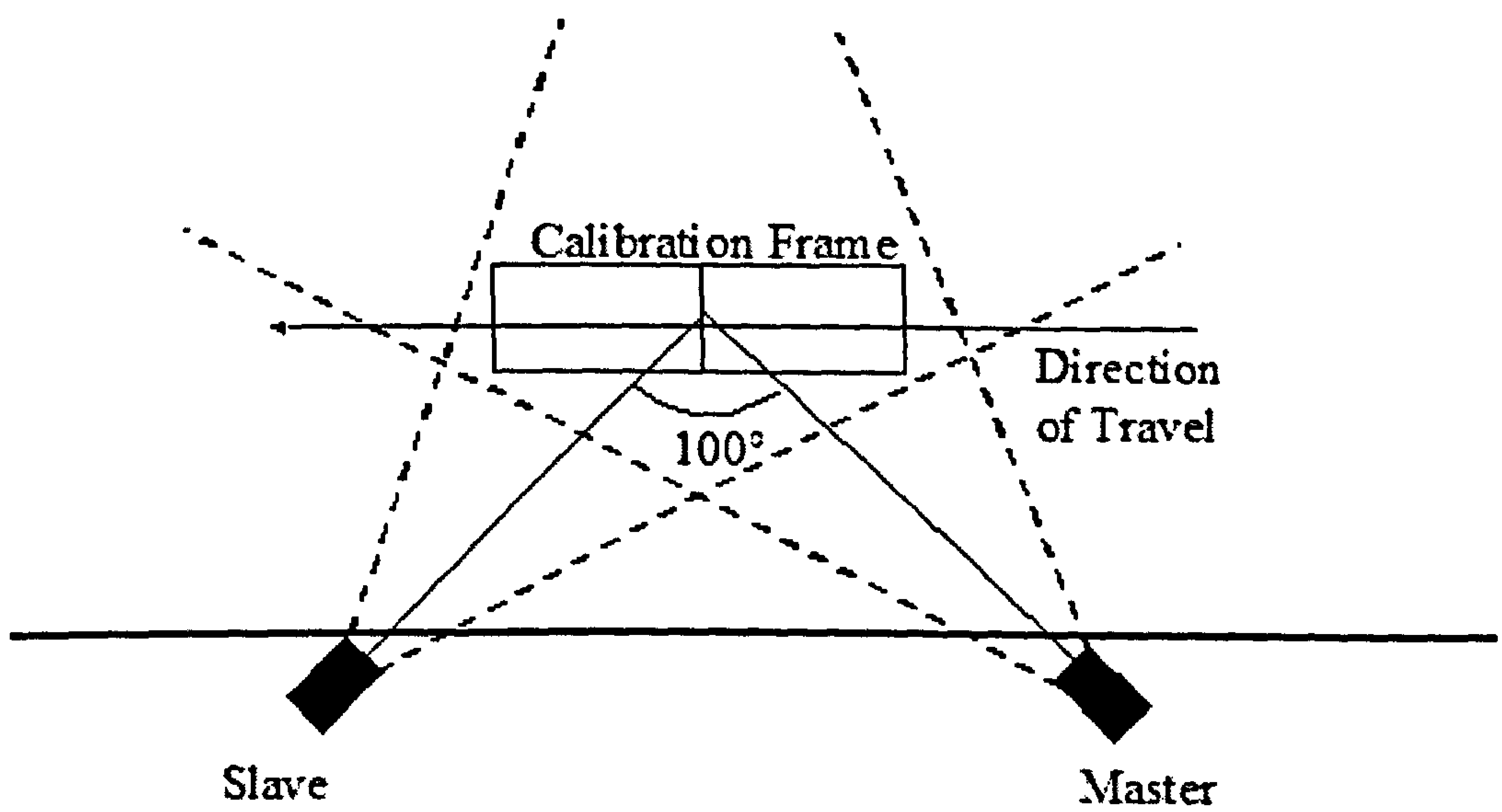


Figure 3.14. Kinematic setup for accuracy assessment of the calibration frame.

Following collection the footage was captured into Peak Motus 32 motion analysis software and the calibration points digitised. Accuracy of the frame on-water was assessed in two ways, initially the percentage volume errors produced from the DLT reconstruction were inspected to ensure the error in reconstruction did not exceed 1% of the calibrated volume (Angulo and Depena, 1982). The second method used trigonometry to determine the accuracy of the calibration frame. After the reconstruction of the frame had been completed, the markers within the frame were used as a series of five right angle triangles were digitised using calibration markers within the calibrated volume.

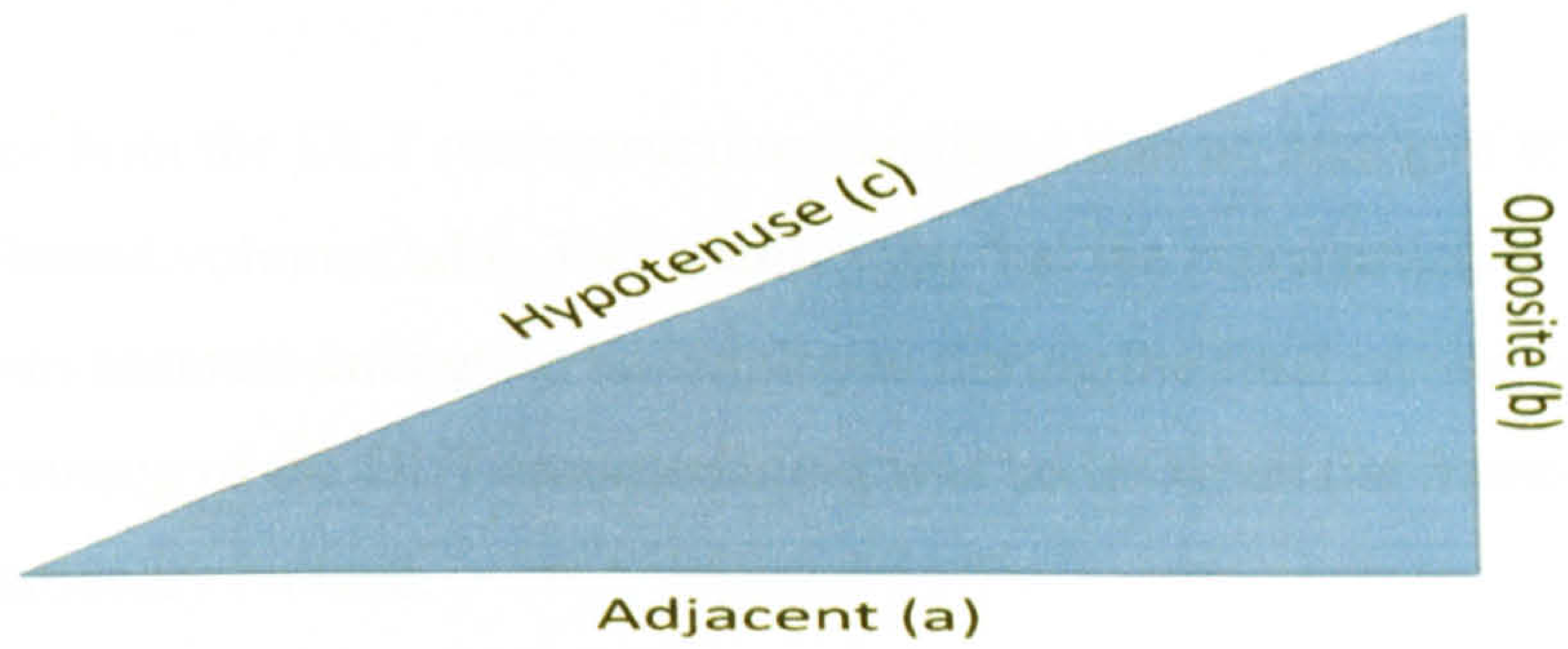


Figure 3.15. Trigonometry of a right angle triangle.

$$a^2 + b^2 = c^2$$

It was ensured that one side of each triangle equated to the measurements provided for the dimensions of the calibration frame. The triangles incorporated all planes within the calibrated volume and were digitised over 50 frames (figure 3.16). The dimensions of the triangles varied and are outlined below (table 3.3):

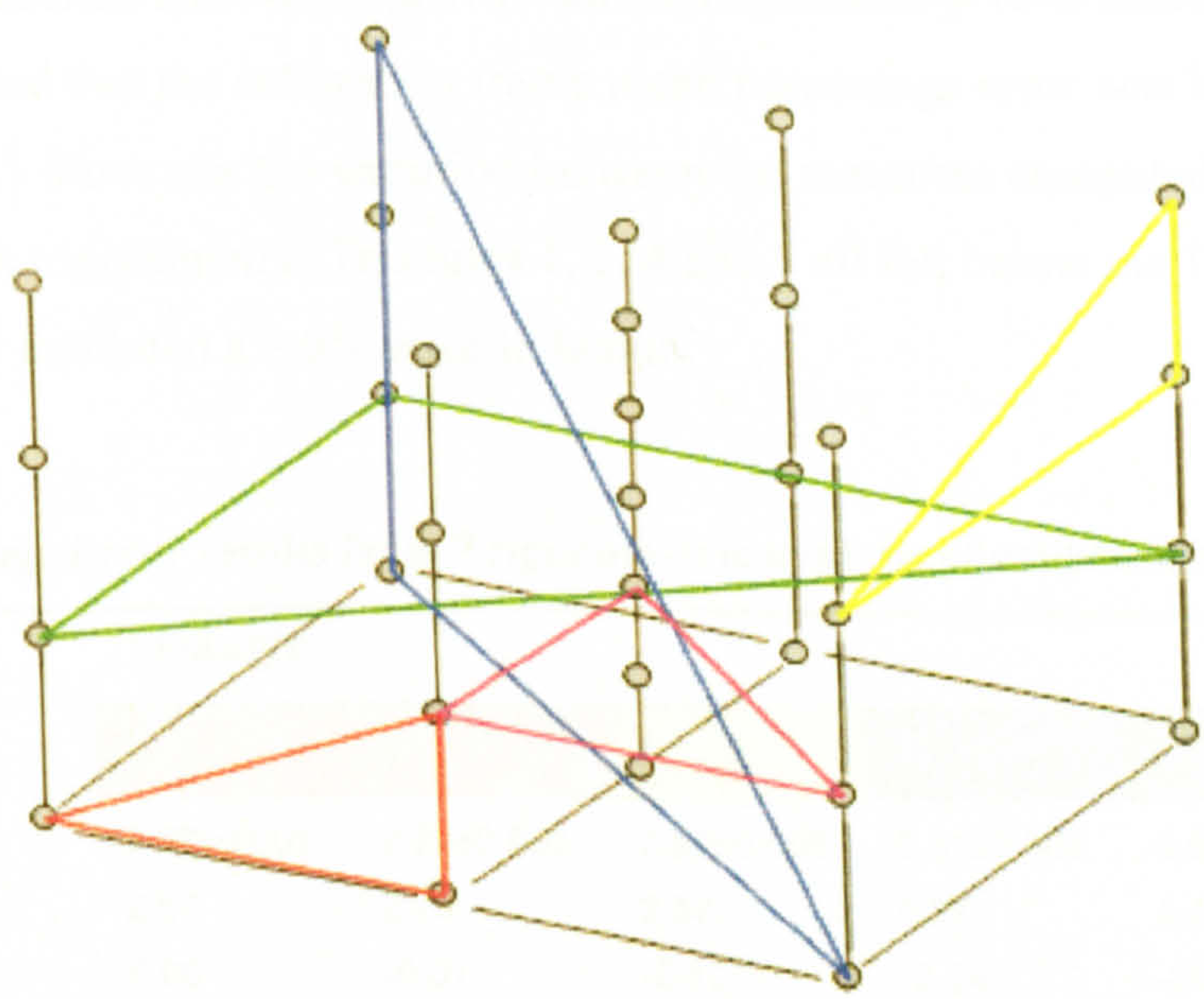


Figure 3.16. Schematic of triangles used for trigonometric accuracy assessment of calibration frame.

Table 3.3. Dimensions of triangles used to assess floating calibration frame accuracy.

Triangle Number	A	B	C	Colour
1	2.50m	0.60m	2.57m	Red
2	2.50m	1.25m	2.80m	Purple
3	2.50m	0.60m	2.57m	Yellow
4	5.59m	1.80m	5.87m	Blue
5	5.00m	2.50m	5.59m	Green

3.5.3. Exploration of Kinematic Data

The percentage error from the DLT reconstruction identified that no resultant errors were higher than 1% of the calibrated volume (table 3.4), identifying that the reconstruction of the calibration frame was accurate enough to be employed during the final testing protocol. Interestingly the accuracy of the DLT reconstruction was better when the frame was floating on-water than when stationary on land.

Table 3.4. Resultant and planar mean percentage of volume errors from the DLT reconstruction of the calibration frame accuracy on-land and on water.

	Mean			
	X	Y	Z	Resultant
Half Frame on Land	0.189 ± 0.02	0.782 ± 0.13	0.853 ± 0.09	0.630 ± 0.08
Full Frame on Land	0.179 ± 0.02	0.571 ± 0.02	0.990 ± 0.00	0.418 ± 0.01
Full Frame on Water	0.116 ± 0.02	0.542 ± 0.12	0.596 ± 0.16	0.322 ± 0.07

The trigonometric analysis was undertaken from the on-water calibration footage, as it was found to be most accurate and would provide an environmentally valid assessment of the frame. Results demonstrated that the calibration frame mean percentage error was below the 1% threshold. Table 3.5 illustrates the variation between the measures computed and value formulated through trigonometry. Triangles 1, 2, 4 and 5 all fell below the 1% error threshold, however triangle 3 exhibited a 3.9% error in length.

Table 3.5. Percentage Error results from Trigonometric analysis of calibration frame.

	Triangle					
	1	2	3	4	5	Mean
Mean (±SD)	2.57±0.001	2.80±0.003	2.67±0.006	5.91±0.002	5.59±0.003	2.97±0.004
Actual measurement (m)	2.57	2.79	2.57	5.87	5.59	2.95
Variation (m)	0.00	-0.01	-0.10	-0.04	-0.00	-0.03
% error	0.02	-0.28	**-3.91**	-0.67	-0.03	-0.91

Coloured backgrounds equate to coloured triangles in figure 4.14. (full data set in appendix E)

The error identified in the 3rd triangle was unexpected as the basic analysis of the accuracy of the calibration frame from the computed errors of the planes was identified as 0.322% (table 3.4). The mean error across all triangles demonstrated that despite the error result from triangle three of the trigonometric assessment the error was 0.91%. Therefore results have ascertained that the accuracy of the calibration frame is sufficient for the current study and is below the 1% error level as established by Angulo and Dapena (1992).

3.6. Summary and Conclusions

The pilot studies identified that the data logger systems with the EMG electrodes, torsiometers and electrogoniometers were suitable for use in a water-based environment. However, there were a number of issues to be addressed to ensure data collected during the research detailed in the next chapter was robust. The major problem during the completion of the pilot work was the synchronisation of the two data loggers. This was overcome with a new development by MIE medical research Ltd. synchronisation switch that transmits an infrared overload signal onto each channel allowing synchronisation of numerous data loggers.

Electromyography results exhibited a number of interesting findings, with the rectus femoris and external obliques presenting clear activation during paddling (figure 3.1). The readings from the EMG channels for the legs were promising enough to continue with their inclusion in the final study, though requiring more accurate application of electrodes on the surface of the belly of the muscles of interest.

The electrogoniometers clearly indicated a relationship between the flexion and extension of the knees and the rotation of the trunk. The electrogoniometers positioned at the hip did not provide viable data as interference with the signal was caused by the electrogoniometer being knocked against the cockpit of the kayak. The issue of hip angle determination was overcome using the law of cosines, a triangle was demined by point at the centre of the knee, centre of the hip and a marker 0.25 m above the centre of the hip joint. This required the knee to be in the field of view when digitising, this was achieved by positioning the high speed video cameras high above the water surface (2.5 m for the final protocol).

Furthermore the pilot work indicated that the alignment of the torsiometer should be optimised for the different trunk rotation positions adopted by individual paddlers. This was addressed by the introduction of a second torsiometer, allowing the application of one torsiometer over the thoracic vertebrae and another over the lumbar region. This solved the initial problem and provided a further opportunity to study the actions of the different spinal regions during paddling technique.

The final issue requiring resolution from the pilot work was the synchronisation of the kinematic, kinetic and data logger systems. The kinematic system sampled at 200 Hz, slower than the kinetic and datalogger systems (500 Hz). However the three systems had no designated way of hardware synchronisation and thus complete synchronisation would have to occur after data collection using event markers within the data collected.

The synchronisation of the multiple analysis techniques was solved by breaking down all data sets into 1/1000 s intervals through insertion of blank rows. After ensuring all data was normalised to isometric maximal voluntary contractions and baselines and separated to 1/1000 s intervals several synchronisation points were derived. The kinematic system was synchronised with the instrumented paddle system by using the point of paddle entry. The frame following paddle water contact was synchronised with a force value of 15 N. To determine which stroke took place in the calibrated volume a Sony Handycam DCR-PC53E digital video camera was used, positioned 2.5 m above the water and was panned throughout the trials to ensure the subject was in frame for the entire trial.

Furthermore synchronisation between the kinematic, EMG and goniometer systems was conducted using the trace from the Latissimus Dorsi and high-speed video. The frame in which the blade of the paddle starts its backward sweep of the stroke would be caused by an extension of the shoulder, due to the locked elbow position. This extension will be caused by a contraction of the Latissimus Dorsi alongside other muscles, therefore this initiation of activation was used to synchronise the various systems. This was chosen as Logan and Holt (1985) identified this synchronisation during their investigation into on-ergometer paddling technique. The varying sample rates of the high-speed video (200 Hz) and the EMG system (500 Hz) resulted in an accuracy within 0.005 - 0.01 of a second for this method.

This chapter and the methods within has produced a detailed consideration of the technical and procedural components of each instrumentation system and their performance and applicability within a water based environment. Furthermore is has enabled the development of a multiple system data collection and analysis procedure that will optimise the possibility of successful investigation of human subjects under environmentally valid conditions. Furthermore the methods outlined will allow the research question to be answered as the entire body can be analysed simultaneously with the protocol developed within this chapter. As a result the method produced within will be employed in the following study to allow an answer to be formulated as to the contributions of the body as a whole during on water paddling.

4. Biomechanical Analysis of Elite Level Flatwater Sprint Kayaking Technique: with specific focus on the Actions and Contributions of the Trunk and Lower Limbs.

4.1 Introduction

International level sprint kayaking is a sport in which performance outcomes are measured by race time. To produce the highest possible average boat velocity a paddler must have an efficient technique and the correct equipment set up. This is apparent in the volume of literature carried out since the 1970's on paddling technique (Yoshio, 1974; Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980; Kerwin *et al.*, 1992; Sanders and Kendal, 1992a; Hay and Kaya, 1998; Baker *et al.*, 1999) and paddle development (Kendal and Sanders, 1992; Kerwin *et al.*, 1992; Sanders and Baker, 1998). Many previous researchers have concentrated on simple factors such as stroke rate and stroke length (Hay and Kaya, 1998), with others investigating more complex factors such as angle of blade entry and point of peak paddle acceleration (Ariel, 1977). Most researchers have utilised kinematics as the predominate research tool, tracking the path of the paddle as a whole (Kendal and Sanders, 1992) or just the blade of the paddle (Sanders and Baker, 1998), as well as the motion of the upper limbs (Campagna *et al.*, 1987; Kerwin *et al.*, 1992).

The predominance in the use of kinematics as a research tool has been a result of an introduction of the wing paddle design, which revolutionised the manner in which propulsion was developed. Leading much previous research to focus on the movements of the paddle and the upper body (Yoshio, 1974; Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980; Kerwin *et al.*, 1992; Sanders and Kendal, 1992a; Hay and Kaya, 1998; Baker *et al.*, 1999). Much of which identified that it is the movement of the upper body and the individual technique employed that would appear to be fundamental in the production of boat velocity.

Early research focused mainly on elite level performance (Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980) highlighting the key phases of technique, the importance of forward reach and the requirement of reaching a vertical paddle position during the stroke. However introduction of the Scandinavian wing blade paddle forced an alteration in technique resulting in these findings being outdated, as the results referred to the greenland flat blade paddle. Sanders and Baker (1998) produced a review paper highlighting six important advantages provided by the use of the wing bladed paddle (see page 17), all concerning the manner and efficiency of kayak propulsion. Sanders and Baker (1998) indicated that the positioning of the paddle and its ability to reduce braking forces at the point of paddle entry were important and theorised that these affected the efficiency of force production. Furthermore mathematical efficiency was determined by Jackson (1995) investigating the vortex production of the wing and flat bladed paddles. The traditional flat paddle blade with its near symmetrical design, relies on drag and vortices formed at the edges of the blade, with a 74% level of efficiency. The evolution of the wing blade has however increased the efficiency of the technique to 89% (Jackson, 1995). This is achieved by the lateral motion of the blade; the blades path through the water sheds a starting vortex and a trailing vortex which form a continuous loop (Jackson, 1995). The result of these vortices means a much larger vortex is produced, twice the size of the vortex produced by the traditional blade, therefore resulting in an increased efficiency (Jackson, 1995). Furthermore an important factor highlighted by Sanders and Baker (1998) was the wing blade's apparent ability to the paddler to keep the blade in the vertical position for a longer period of time. It may be this increased time in the vertical position that may account for the 15% increase in efficiency identified by Jackson (1995).

The 15% increase in efficiency of the paddle identified by Jackson (1995) although important will be ineffectual if technique does not allow for the force to be efficiently developed. Kemecsey and Moll (1998) identifies that efficiency is essential within technique to ensure all spent energies are directed into maintaining a smooth running of the kayak and therefore resulting in high kayak velocity. From this early work Kemecsey and Moll (1998) proposed the application of the concept of tensegrity within paddling technique. Kemecsey and Moll (1998) explain tensegrity as:-

> '... the concept, study and explanation of shapes and structures, through the interaction of tension and compression, ranging from natural forms which may be as small as human cells in the field of biology, to a man-made design as the Amagi Dome in Japan in th field of architecture.'
>
> Kemecsey and Moll (1998), pp. 1.

Kemecsey and Moll (1998) further explain the application of tensegrity within the human body as:-

> 'The bones are the internal compressior system and the muscles and tendons provide local tension. Neither can exist alone.'
>
> Kemecsey and Moll (1998), pp. 1.

Kemecsey and Moll (1998) further explained the application of this concept by, describing aspects of technique as power circles. An example of this was presented within the shoulders, arms and paddle at the beginning of the stroke. The pulling side hand produces a compression against the paddle creating a tension throughout the pull arm and shoulder. The pull side shoulder moves backwards forcing the push side shoulder to move forward, both acting as compression points, and conduits allowing the tension to move across the body to the pushing arm. The tension moves down the push arm to the push hand, which creates a compression against the paddle. Kemecsey and Moll (1998) indicated that the application of tensegrity will therefore provide strong positions allowing efficient force production at the paddle and strong links to the kayak to ensure the force is produced efficiently to propel the kayak forward resulting in an improved performance. This indication from Kemecsey and Moll (1998) supports Kemecsey's (1986) description of technique in which the importance of entire body contribution to performance are outlined. Therefore investigation of paddling technique requires comprehensive analysis techniques combining three dimensional reconstruction, electromyography and kinetic analysis.

An early study investigating the alterations in technique resulting from the wing blades introduction (Kerwin *et al.*, 1992) was conducted using the first three dimensional kinematic analysis. Kerwin *et al.* (1992) analysed technique of national level paddlers using both flat and wing blade paddles using a similar phasing system identified by Plagenhoef (1979). Kerwin *et al.* (1992) identified 3 phases within both the left and right side (figure 5.1) whilst attempting to develop an analysis system that could be utilised as a training and coaching tool based at the National Water Sports Centre at Holme Pierrepont, Nottingham. Additionally Kerwin *et al.* (1992) aimed to compare the differences the development of the Scandinavian wing paddle would have on technique. Kerwin *et al.* (1992) used 6 subjects, 3 using both wing and flat blade paddles while the other 3 used either the wing or flat blade paddle only. The footage was collected from two cameras placed on the same side of the regatta lake 125 m apart so the optical axis would be at 90° and intersect at the midpoint of the calibrated space. Calibration was attained using markers placed along the far side of the regatta lake at 10 m intervals to ensure that there was always reference for the digitisation process. Data collected were analysed similarly to the methods of Plagenhoef (1979) digitising the paddle path, analysing the stoke time, kayak velocity, stroke frequency, distance per stroke, percentage of time in each phase, lateral displacement of the blade tip and as Mann and Kearney (1980) the velocity of the centre of mass of the kayak and performer combined.

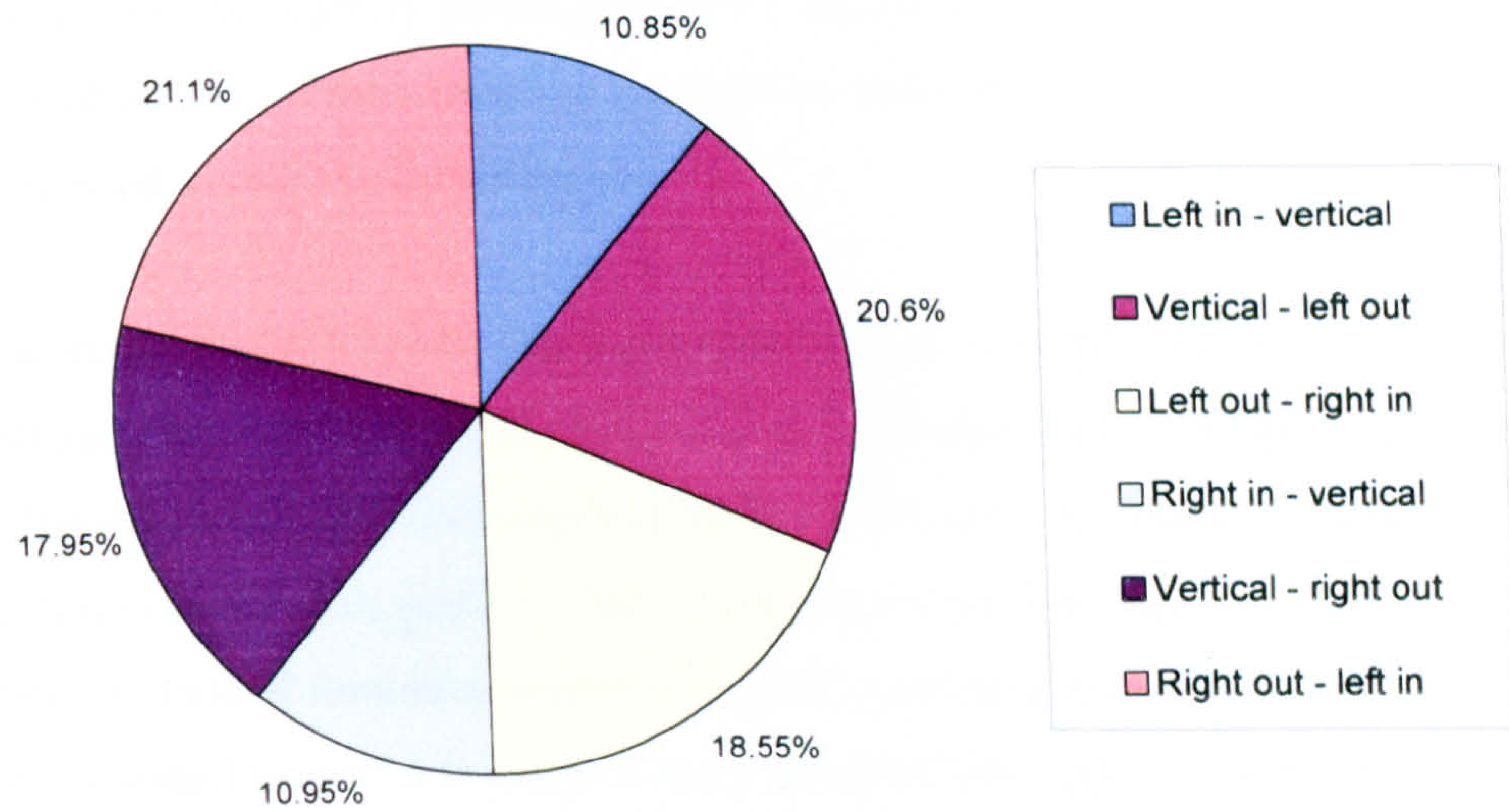


Figure 4.1. Kerwin, Atkins and Williams (1992) phases of technique.

Technique findings highlighted the differences found between the two paddle types, the flat blade and the Scandinavian wing paddle. The major difference was the stroke rate. Kerwin *et al.* (1992) identified a higher stroke rate when using the wing blade paddle (57 strokes per minute wing blade compared to 47 strokes per minute flat blade). This had a clear effect on the peak acceleration (7 $m.s^{-2}$) and the average kayak velocity, 4.79 $m.s^{-1}$ (wing paddle) and 4.18 $m.s^{-1}$ (flat blade). Kerwin *et al.* (1992) findings indicated that the development of paddle design from the previously used flat blade paddle to the Scandinavian wing paddles has resulted in a number of changes in technique, including increased lateral motion of the blade and reduced paddle water contact time. This research therefore supported that the evolution in technique is clearly due to the advancements in paddle design (Sanders and Baker, 1998).

Kerwin *et al.*'s (1992) application of three dimensional analysis provided greater detail than preciously achieved through kinematic analysis, however some limitations were apparent within the research. A minor limitation was the positioning of the cameras on the same side of the performer resulting in a greater accuracy in near side analysis. As at a number of points during the stroke cycle the blade and some joint centres on the far side to the camera would depend on estimation. Kerwin *et al.* (1992) acknowledged this but considered it an acceptable error. This may have impacted upon the findings of the study and exaggerating asymmetrical findings in paddling technique. The asymmetrical observation by Kerwin *et al.* (1992) may have been due to a poor technique used by the paddler as the force production of paddlers has been found to be asymmetrical (Lovell and Lauder, 2001), or may be a data collection artefact due to the cameras being positioned on the same side of the paddler, though reconstruction techniques can compensate for missing marker points. The main limitation was the accuracy of the reconstruction from the markers positioned on the far bank of the regatta lake. These markers were positioned outside of the motion of the paddler and with no indication of how these markers were used to reconstruct technique.

Following Kerwin *et al.* (1992) further three dimensional analysis has been conducted by Baker *et al.* (1999) and Ong *et al.* (2005) investigating the influence of gender and equipment setup on technique. Baker *et al.* (1999) investigating differences between male and female paddlers with focus on differences between genders that would impact on coaching techniques. Ten national level paddlers (6 male, 4 female) completed 3 trials consisting of a 200 m acceleration phase, prior to the calibrated area which was 6 m long and 2 m high and 2 m wide, though no indication what type of calibration object nor its accuracy were provided. Subjects were asked to paddle at the equivalent speed of the national championship winners in the 1000 m for the men and the 500 m for the women (speeds not reported). Footage was collected using two gen-locked S-VHS video cameras operating at 50 Hz, with the shutter speed set at 1/1000 of a second. The middle knuckles, wrists, elbows and shoulders on both left and right sides were digitised, with the addition of two markers on the shaft, two at the neck between the hand and the blade of the paddle and two further markers, one on the bow of the kayak and the other on the stern. The direct linear transformation (DLT) (Abdel-Aziz and Karara, 1971) method was used to produce a three dimensional reconstruction of the points, over which a quintic spline was used to smooth the data, using ten frames pre and post the cycle of interests to minimise end effects. The analysis was then undertaken using the opinion of two coaches and findings in previous literature as tools to identify which variables would be measured.

The analysis was separated into right and left sides. Within each, both total and intra-stroke velocities, timing and displacement measures, two and three dimensional measures of the entry and exit angles, and trunk rotation (represented by shoulder rotation) were investigated. The findings indicated that there was a significant difference between males (4.94 ± 0.17 m.s^{-1}) and females (4.50 ± 0.33 m.s^{-1}) in velocity ($P = 0.01$) and intra-stroke velocity, therefore a significant difference in distance covered during stroke (male = 2.66 ± 0.19 m, females = 2.47 ± 0.16 m; $P = 0.03$) and glide (male = 1.04 ± 0.06 m, female = 0.93 ± 0.09 m; $P = 0.01$) was reported. There was however no significant difference identified in the spatial analysis, therefore suggesting that techniques between genders were similar and that adoption of different training technique for males and females was unnecessary. Baker *et al.* (1999) stressed that their findings were only part of a preliminary study as the group sizes were small (6 males and 4 females) and so may have influenced the statistical analyses, which were not described. A limitation with the paper is that although the ability to produce high speed analysis was available, the footage was recorded at 50 Hz which would not have been fast enough to ensure that all important events during the cycle were captured. The shoulder rotation would have been an exaggerated measure of trunk rotation as the degree of rotation may vary at different points in the spinal column, which would have been further affected by any extension and flexion of the hips and or knees during the paddling cycle. However, the fact that the authors did take into account the degree of trunk rotation is an important signpost in acknowledging that the trunk plays and integral part of the technique and supports the inclusion of trunk rotation measures in the research detailed in this thesis.

More recently a study by Petrone *et al.* (2006) further investigated trunk rotation during paddling, with specific focus on on-ergometer paddling technique. Petrone *et al.* (2006) further developed the analysis through the use of kinetics in an attempt to determine key technique variables linked to performance levels. Using female elite level paddlers (n = 5) Petrone *et al.* (2006) measured the patterns of motion in the upper body, flexion of the knees and the force imparted onto the footplate using a specifically assembled dynamometric footpad (Petrone *et al.*, 2006). Subjects were prepared with markers on all major upper body joints with further markers on the head, paddle, 7th cervical and 12th thoracic vertebrae, and the left and right Posterior Superior Iliac Spine. Furthermore rotational potentiometers were attached to the knees to measure changes in knee angle during paddling and video footage was collected using 6 infrared coaxial 50 Hz cameras. Subjects then completed 4 trials under different conditions:

1. Fixed seat at 70 strokes per minute;
2. Fixed Seat at 90 strokes per minute;
3. Rotating seat at 70 strokes per minute;
4. and, Rotating seat at 90 stroke per minute.

From each trial 50 stroke cycles were collected, ten of which were selected for further analysis. Kinematic data was digitised to provide trajectories and angles of the paddle and appropriate segments. However, results presented by the authors are limited, providing values for just 2 subjects (S1 - Olympic K1 500m Gold Medallist and S5 - K2 National 5000m champion) for comparison in paddle motion. All paddlers trunk rotation values were presented, with only S1's knee flexion and force values available to the reader.

Paddle trajectory results reported asymmetry between sides in all paddlers, with the comparison between S1 and S5 indicating a wider stroke for S1 and longer paddle path. Force characteristics and knee motion presented for S1, exhibited greater knee flexion in the right knee for all conditions, with the rotating seat (70 spm and 90 spm – Left 63°, Right 65°) causing greater flexion than the fixed seat condition (70 spm – Left 65°, Right 71° and 90 spm – Left 66°, right 72°). Little difference was found between right and left force production with no pattern of either right or left imparting greater force. The rotating seat exhibiting clearly higher force values than the fixed at both 70 spm (Fixed, L - 253 N, R - 264 N, Rotating, L - 362 N, R - 355 N) and 90 spm (fixed, L - 319 N, R - 320 N, Rotating, L - 465 N, R - 46 N). Trunk rotation highlighted that subjects 1 and 4 exhibited the greatest symmetry, with all other paddlers showing asymmetrical results.

Petrone *et al.* (2006) concluded that despite variation in ability all paddlers exhibited factors that can be improved upon within technique and that the kinetic and kinematic parameters were correlated with skill level; no indication of the correlation techniques or statistical evaluation are reported. Petrone *et al.*'s (2006) conclusions are limited and not supported within the paper as only a selection of the findings are presented. Further to this a number of limitations exist within the method and presentation of findings. Firstly, no acclimatisation was provided for the subjects, this could have caused variations in technique, as the paddlers may have been uncomfortable with the extensive preparation. This is alluded to in the discussion though no effort was made to overcome the possible restriction of movement. Therefore any future investigation consisting of such extensive subject preparation would require an acclimatisation period to ensure technique representative of natural paddling. Furthermore the use of an ergometer could influence paddling technique (Fleming *et al.* 2007) when compared to on water paddling. Petrone *et al.* (2006) 'consistently' selected 10 cycles from the 50 collected but determined no criteria for the selection of these cycles. This is important as in later cycles paddlers' technique could deteriorate, especially at 90 spm, due to fatigue. This could further be affected by the distance over which the paddlers compete, with 500 m paddlers coping with the high stroke rates better than the 1000 and especially 5000 m paddlers. This might explain the differences in paddle movement reported between S1 (500 m Olympic Gold) and S5 (5000 m national champion).

Therefore the findings presented by Petrone *et al.* (2006) hold little application within the general kayaking population, however a number of the factors within the study raise important issues within technique. Petrone *et al.*'s (2006) measurement of trunk rotation reinforced the acknowledgement of the trunks contribution to technique suggested by Baker *et al.* (1999). However Petrone *et al.* (2006) displayed further insight into technique through the investigation of leg extension during paddling, as well as the importance of force production during paddling. Following Petrone *et al.* (2006), Fleming *et al.* (2007) investigating muscular sequencing of the quadriceps, anterior deltoid, triceps brachii and latissimus dorsi during on water and on-ergometer paddling technique. Elite level flatwater kayakers (n = 14) completed matched exercise protocols, paddling at 75, 85 and 95% of $\dot{V}$ O2max for a duration of 3 minutes, whilst video footage was collected at 50 Hz.From the protocol 10 consecutive paddle strokes were selected for analysis, with latency, duration, peak activity and timing of peak activity were analysed.

Results identified monopahsic and biphasic activation patterns within the muscles, the triceps brachii and anterior deltoid displaying biphasic patterns and the quadriceps and latissimus dorsi monophasic. Further investigation identified peak deltoid activity during the second phase was significantly ($P < 0.01$) greater during on-ergometer paddling (19.6 ± 2.6 μVs) in comparison to on-water (7.6 ± 1.1 μVs). Furthermore peak activity of the quadriceps occurred at 125 ± 12 ms during on-ergometer paddling, identified to be significant earlier than during on water paddling (193 ± 15 ms, $P < 0.01$). Further significant findings were demonstrated by the triceps brachii, which displayed significantly shorter activity during the first phase activity (on-ergometer 414 ± 17 ms; on-water 480 ± 20, $P < 0.01$), whilst overall activity of the triceps brachii, as a percentage of the paddle stroke, was identified to be significantly greater during on-ergometer paddling (on-ergometer: $59 \pm 4\%$; on-water $68 \pm 5\%$, $P > 0.01$).

Fleming *et al.* (2007) identified further significant findings between the three increasing intensity levels. The peak activity of the phase 1 triceps was found to be significant and increased concurrently with exercise intensity (75% 14 ± 0.9 μVs; 85% 17.3 ± 1.0 μVs; and 17.6 ± 1.2 μVs, $P < 0.01$). This finding was mirrored in the second phase of triceps brachii activation (75% 11.0 ± 0.9 μVs; 85% 13.0 ± 1.2 μVs; and 14.5 ± 1.2 μVs, $P < 0.01$). Finally the quadriceps femoris displayed significant increases along with the exercise intensity, with peak activation increasing from 3.4 ± 0.2 μVs at 75%, 3.9 ± 0.2 μVs at 85% to 4.6 ± 0.3 μVs at 95%. Results would therefore suggest that at higher levels of intensity the power development occurs in the quadriceps, with the triceps being worked harder to control the motion of the blade through the water. Thus providing support to Kemecsey's (1986) theory that a leg drive is a key within paddling performance. However Fleming *et al.*'s (2007) conclusions focused on the variation in the anterior deltoid, suggesting that the significant increase in activation was a direct result of the mechanics of the Dansprint ergometers' pulley loading system, however little explanation was provided for the other significant variations identified.

The findings of the study were limited due to the testing protocol. Most importantly, studies by Kerwin *et al.* (1992) Petrone *et al.* (2006), and Lovell and Lauder (2001) all demonstrated that paddling is an asymmetrical motion, however Fleming *et al.* (2007) assumed symmetry, only analysing one side of the body therefore limiting application of some findings. Furthermore elite subjects were used though no indication of how this ability level was quantified whether it is through level of experience or achievement. Additionally the use of maximal oxygen uptake as a measure of intensity is unusual, as it poses the question of how this was determined during on-water paddling. This could have easily been substituted by using stroke rates rather than percentages of $\dot{V}O_2max$. Therefore the author cannot be certain that the subjects were working at the designated aerobic levels during on-water testing.

The study conducted by Fleming *et al.* (2007) although limited in the methods, highlighted the important technique information that can be gained from the application of electromyography (EMG) during paddling. Prior to Fleming *et al.* (2007) only a single study has investigated technique through the application of EMG had been conducted (Logan and Holt, 1985). Logan and Holt (1985) approached the analysis of kayaking technique by identifying the muscles and their actions involved in the movements during paddling. As previously (Plagenhoef, 1979) the stroke cycle was broken down into 4 phases using kinematic footage. Logan and Holt (1985) highlighted the use of the entire body and its application to performance with the legs, trunk and arms all contributing during the technique cycle.

Findings indicated that strength and speed would be an additional advantage for elite paddlers, however only as an addition to sound technique, otherwise large applications of power in an inefficient pattern will be detrimental to performance. Although the Logan and Holt (1985) paper appears to provide a good notational analysis of the technique at a muscular level, the reliability when applying the information to on-water performance is poor as the analysis was carried out using a kayak ergometer, which although may be accurate when analysing technique with the traditional blade (Campagna, *et al.* 1982 and Campagna *et al.* 1987) the same may not be said when comparing to the wing paddle, as identified by Fleming *et al.* (2007).

The research conducted by Logan and Holt (1985), Baker *et al.* (1999), Petrone *et al.* (2006) and Fleming *et al.* (2007) highlighted early indications that the trunk and legs in conjunction with the upper limbs could be instrumental during performance. Furthermore the application of electromyography by Fleming *et al.* (2007) and the measurement of force production by Petrone *et al.* (2006) further impress the importance of using multiple systems when analysing technique. The application of force analysis has been previously conducted by a number of researchers (Stothart *et al.*, 1987; Aitken and Neal, 1992; Mononen *et al.*, 1994; Mononen and Viitasalo, 1995; Logan *et al.*, 1997) idicating that although average boat velocity is the most important factor in performance, it is equally important to understand the components used to develop velocity. One of these key components is suggested to be force development, with a number of researchers (Plagenhoef, 1979; Mann and Kearney, 1980; Robinson *et al.*, 2002) indicating that:

> '...in no other comparable on-water sport is the relationship between absolute force development and the manner of its production more critical to the final outcome than sprint canoeing and kayaking...'
>
> Robinson *et al.* (2002) pp. 68.

This proposition formed the basis for the evolution of the wing paddle which increased the efficiency of force production (Jackson, 1995). Therefore understanding of force production will aid and enhance performance and the understanding of factors underpinning performance. This has lead to a limited number of studies investigating the application of different techniques to measure force production during paddling (Aitken and Neal, 1992; Mononen and Viitasalo, 1995; Petrone *et al.*, 1998) and measurement of performance (Zsidegh, 1981; Marhold and Herrmann, 1989; Mononen *et al.*,1994; Logan *et al.*, 1997; Ong *et al.*, 2006).

Stothart *et al.* (1987) in an early attempt to determine force production during paddling aimed to develop a system for quantifying on-water stroke force development which could be used during competitive events. Stothart *et al.* (1987) set out a detailed 11 point list of specifications that the paddle must adhere to for it to be suitable for use in competitive events. The system was developed to be used with both kayaking and canoe paddles, with force transducers positioned in the same Wheatstone bridge formation as Aitken and Neal (1992). The system consisted of a telescopic paddle shaft to allow for the paddle to be used by all paddlers. Foil strain gauges were applied in a Wheatstone bridge formation between the grip and blade. Data were transferred through radio telemetry to transmitting from paddle to receiver, which sampled at 150 Hz per channel.

Stothart *et al.* (1987) concluded that the paddle produced was successful and met all criteria set out in the 11 point list of specifications. However Stothart *et al.* (1987) reported no testing protocol or statistical analysis of tests ensuring the data collected from the paddle was reliable and accurate. Stothart *et al.* (1987) do highlight that the system had a number of limitations; firstly the system worked only for 500 m events or shorter, therefore only applicable for a small portion of elite paddlers. Furthermore the radio telemetry system was set in the commercial range at 98.6 MHz, therefore if the testing session was set in an area which is highly polluted with radio-frequencies the system would register large amounts of noise.

Aitken and Neal (1992), similarly to Stothart *et al.* (1987) investigated the forces produced during on water performance through the use of force transducers placed upon the shaft of the paddle. However the strain gauge force transducers were at each end of the paddle between the point of force application of the hand and the blade of the paddle (see figure 4.2). The strain gauge force transducers therefore measured the flexion in the shaft of the paddle, from which the force profiles were determined.

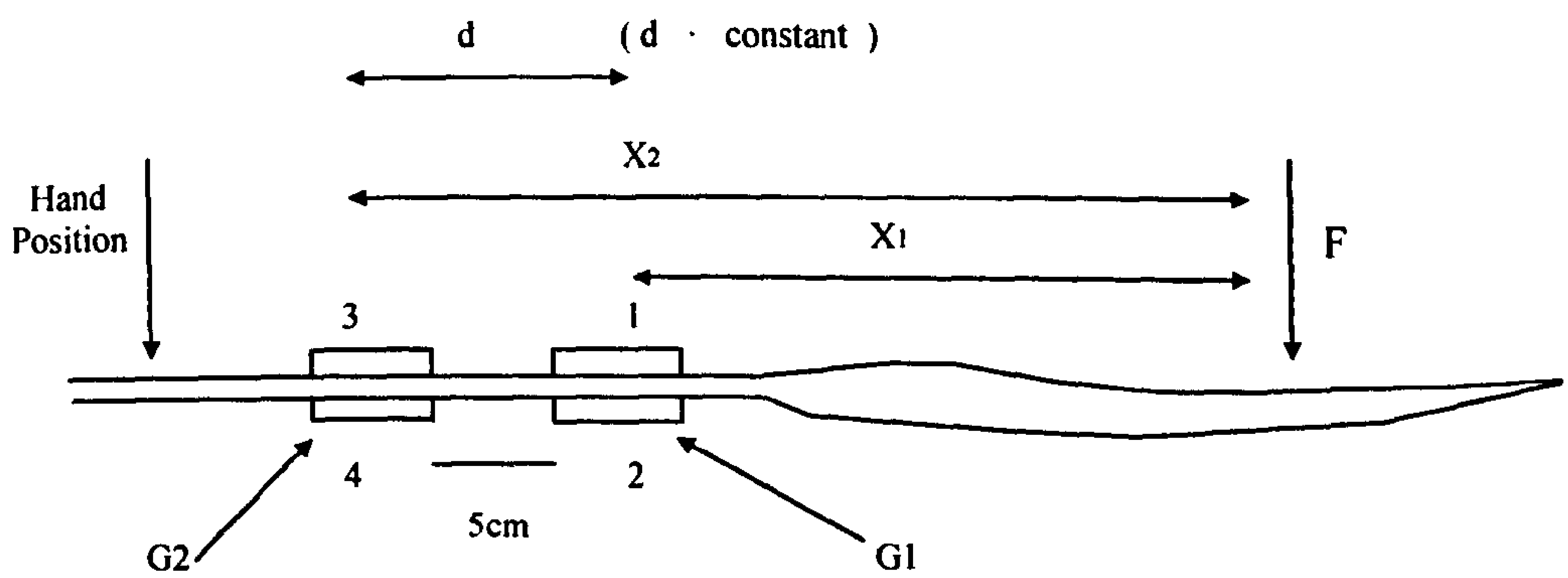


Figure 4.2. Depiction of the position of the strain gauges and schematic model of force determination via resistive change in the Wheatstone bridge. Gauges 1 and 3 measure elongation and gauges 2 and 4 measure compression (adapted from Aitken and Neal, 1992).

The paddle was calibrated through the use of weights ranging from 5 to 30 kg being placed at the centre of the blade, while the fixed position was determined by the position at which the hand would be found during paddling. This calibration was carried out on each paddle used and for each end of the paddle as uniform construction of the paddle shaft could not be assumed. Findings of the calibration identified strong linear relationships between the force applied (0-300 N) and the deformation in the Wheatstone bridge configuration ($r = 0.99$). The calibrated paddle was then used to record force profiles from sub-elite paddlers throughout a 500m race during a training session.

Aitken and Neal's (1992) findings were illustrated through the use of mean peak force, impulse, time to peak force and wet time of the paddle for both the right and left blades. Peak force was identified as 200.6 ± 7.9 N and 213.5 ± 9.6 N for the left and right blades respectively with an impulse reading of 48.7 ± 0.7 Ns for the left and 51.1 ± 1.1 Ns for the right blade. These findings reinforced findings of an early study by Zsidegh (1981) who previously identified this imbalance (see figure 4.3) and a later study by Lovell and Lauder (2001).

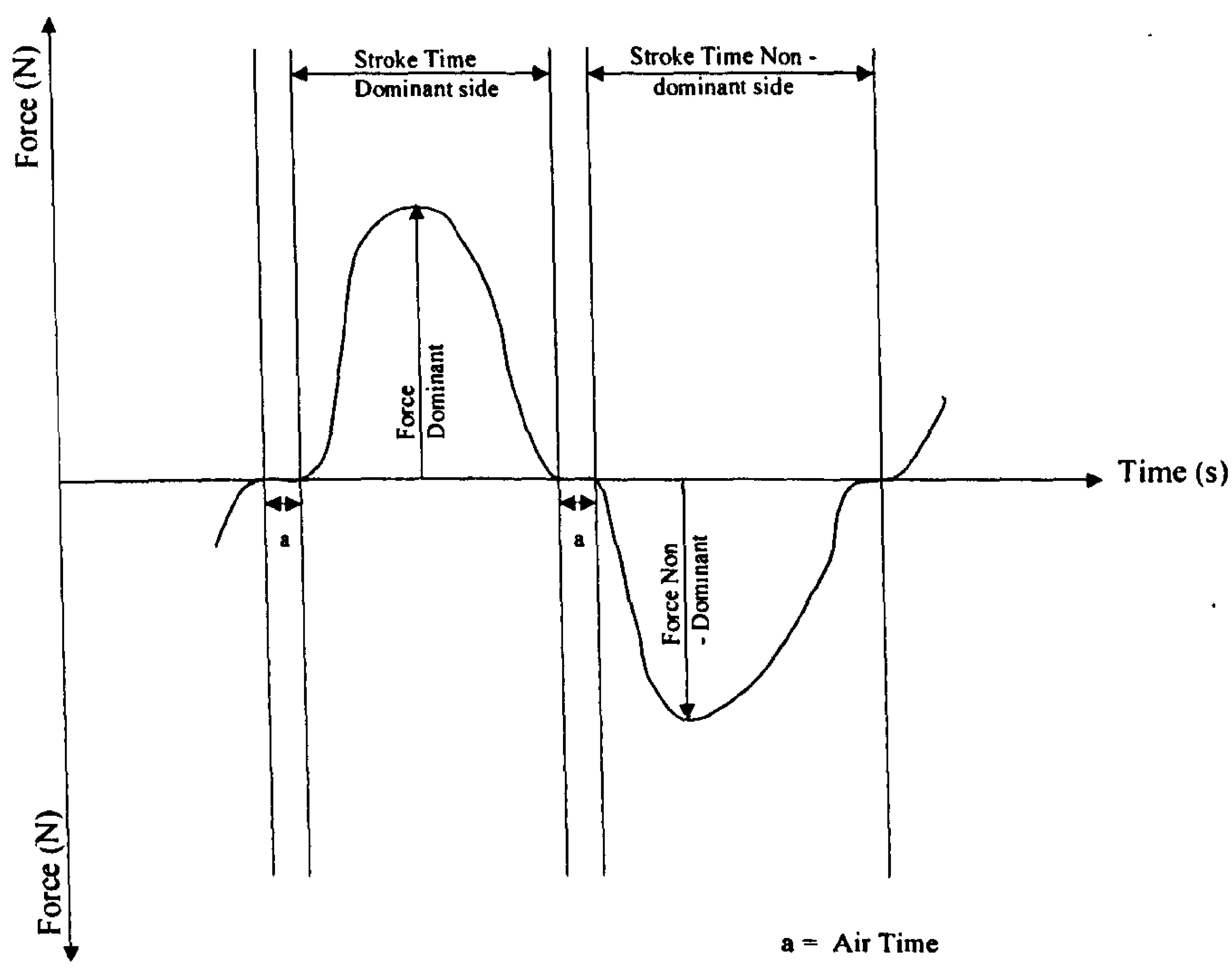


Figure 4.3. Adapted force trace from Zsidegh (1981)

Aitken and Neal (1992) reported that the readings from the paddle were reliable and therefore that a useful tool for analysing the paddle force characteristics and for coaching of kayak paddlers had been developed. The limitations of the system were clearly indicated in that the feedback was not real time and so it would have to be used retrospectively after training and testing sessions. Furthermore Aitken and Neal (1992) identified the limitation in the telemetry system in that 9 channels would be required to be used over a distance of 1000 m for the system to be used effectively for real time analysis.

Although Stothart *et al.* (1987) and Aitken and Neal (1992) developed systems that recorded force during on water paddling the relationship between force and velocity was still to be established in accordance with the theory proposed by Plagenhoef (1979), Mann and Kearney (1980) and Robinson *et al.* (2002). Petrone *et al.* (2006) while investigating the effects of seat design on ergometer performance identified peak values of force production ranging from 253 N to 465 N. However, due to the use of an ergometer no velocity comparisons with force could be drawn. The only researchers to investigate this relationship are Mononen *et al.* (1994) and Mononen and Viitasalo (1995).

Mononen and Viitasalo (1995) investigated force-time parameters and kayak velocity in a single Olympic gold medallist over a 200 m sprint. Specially designed force transducers positioned perpendicular to the plane of the blade, were utilised sampling at 250 Hz and stored using a

MEGA electronics Ltd data logger. Data was collected over a 200 m distance, excluding the first 10 strokes, deemed to be accelerations strokes. Data was statistically analysed using a Pearson correlation coefficient to determine relationships between mean kayak velocity and paddle force parameters. Highly significant ($P > 0.001$) correlations were found between mean kayak velocity and stroke time ($r = 0.86$), stroke end time ($r = 0.84$) (defined as the time from peak force to the end of the stroke), mean paddle force ($r = 0.79$) and peak paddle force ($r = 0.70$). However only a very low lowest correlation was exhibited between force impulse and mean kayak velocity ($r = 0.30$). These findings provide a clear evidence of a positive relationship between stroke rates and mean kayak velocity and mean stroke force values and mean kayak velocity, something that may have been expected. This provides a strong basis for further research; as the findings are from a case study investigation need to be re-examined through analysis of multiple subjects to corroborate findings to improve their applicability to general kayaking populations.

The use of a case study research design limits the immediate applicability to general kayaking populations and other elite level paddlers, but as previously mentioned offers interesting findings for consideration. Furthermore, the method of using the mean kayak velocity, though widely accepted as the key factor of performance (Kendal and Sanders, 1992; Sanders and Kendal 1992a; Hay, 2002; Smith and Loschner, 2002) and not investigating the variations throughout the duration of the pull phase, may explain some of the findings.

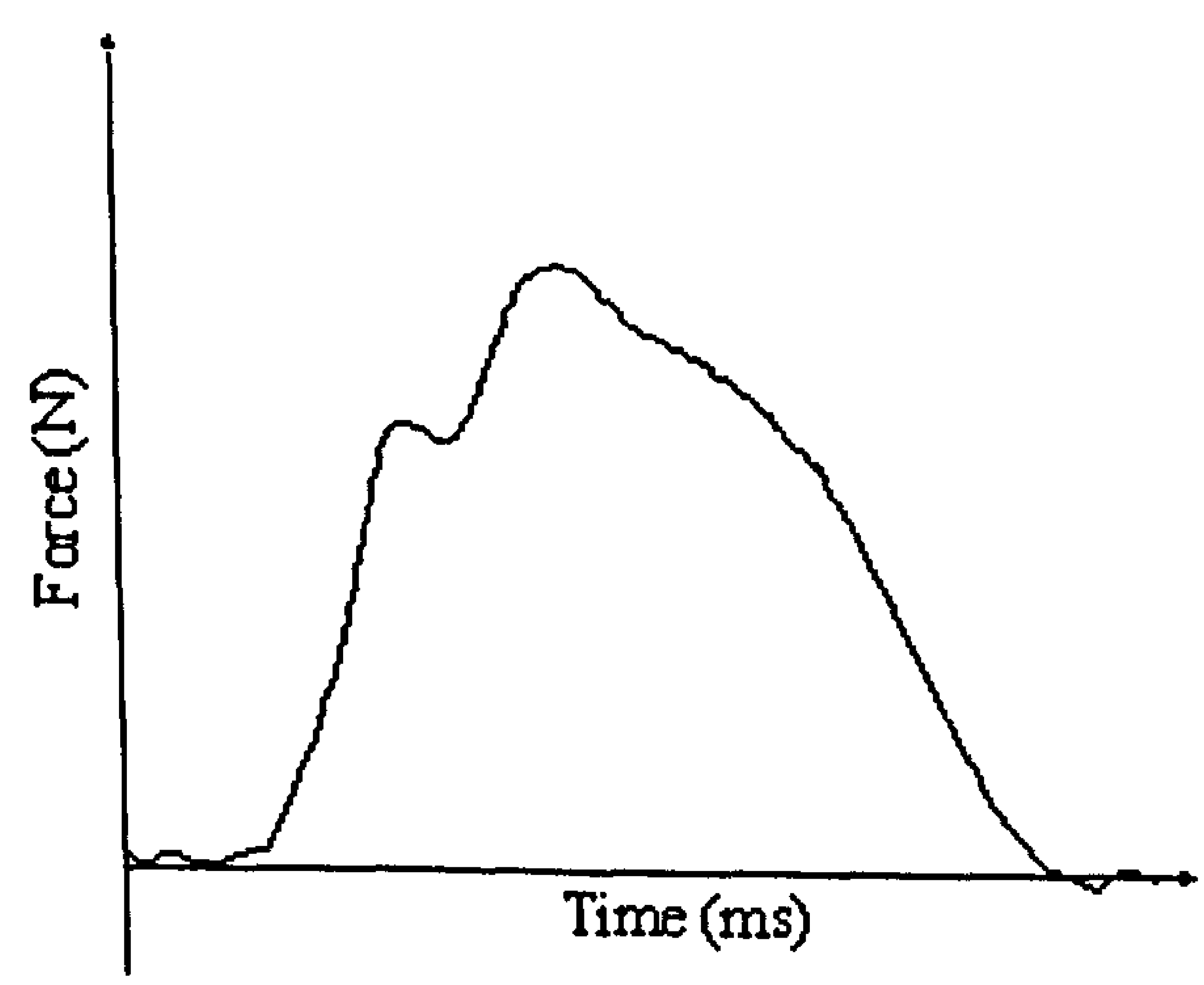


Figure 4.4. Example of force time curve for paddling adapted from Mononen and Viitasalo (1995).

Figure 4.4., an example of the typical curve collected by Mononen and Viitasalo (1995), presents an interesting finding with each paddle stroke exhibiting an initial peak prior to the main propulsive peak, not previously identified by Aitken and Neal (1992). The initial peak

appears similar to that of an 'impact' peak in running which is caused by the slapping of the paddle against the water. This displays a weakness within the technique as a smooth rapid production of force would be advantageous. This 'impact' peak could be the cause of the large variation in the velocity of the kayak during the stroke identified in the results, by causing a breaking force at the beginning of the stroke.

This breaking effect can be identified to by the 'impact peak' and the dip in boat velocity occurring simultaneously. Furthermore the 'slapping' action that causes the 'impact peak' identified in the force traces may cause disruption of the water into which the paddle is entered would negate the theory of finding still water proposed by Sanders and Baker (1998). Another limitation of the study is in the provision of methodological explanation, with minimal explanation of calibration and analysis procedures, therefore reducing the ability to replicate and interpret the results.

Mononen *et al.* (1994) utilised the same techniques as Mononen and Viitasalo (1995) to investigate force-time characteristics on stroke time, peak forces and impulses during 200 m sprints in K2 kayaking. The main aim of the study was to determine the applicability of using a force analysis system to monitor performance during training. A sub aim was to determine any differences in force production between front and back paddlers in K2 paddling, hypothesising that there would be no significant differences in force production between front and back seat paddlers in K2. Subjects consisted of National level kayakers (n = 2) who completed four 200 m maximal paddling sprints with 15 – 20 min rest intervals. (It should be noted that prior to competing in the K2 the front paddler was Olympic and World Champion in K1). Front and back paddlers exhibited identical cycle times (922 ± 26 ms). The half cycle time (pull and glide on one side) did show slightly different time for the front and back paddlers. The front paddler displayed no differences (right: 460 ± 2 ms; left: 460 ± 14 ms) between half cycle time, however the back paddler exhibited an asymmetrical paddle stroke, with the left half cycle shorter (442 ± 15 ms) than the right (476 ± 25 ms). Additionally an average increase of 8% in stroke rate was evident as the trial progressed, supporting the suggestion by Plagenhoef (1979) suggestion that at the end of a race paddlers produce a 'spurt' or increase in stroke rate.

Force characteristics also displayed differences between front and back paddlers, with the front paddler producing 20% higher values than the back paddler on the right side and 8% greater on the left side. However both subjects exhibited similar declines in peak force production during the 200 m sprints. Impulse values were calculated from force-time curves, with the front paddler producing higher impulses by up to 14%. The results lead Mononen *et al.* (1994) to conclude that the system was suitable for use during training and preparation as a tool for monitoring progress and performance. However as Mononen *et al.* (1994) used the same system as Mononen and Viitasalo (1995) and as previously, a limited explanation of calibration of the force analysis system is presented, stating only, 'voltage related to physical values'. Furthermore the use of limited subject numbers again reduces the application of findings to general kayaking K2 populations. This may be further skewed by the individual differences in skill and experience levels between the former Olympic and World champion and a younger less experienced K2 paddler that were used within the investigation.

The high levels of force identified by Aitken and Neal (1992), Mononen *et al.* (1994), Mononen and Viitasalo (1995) and Petrone *et al.* (2006) are required bilaterally at a frequency between 60-70 times per minute, therefore placing extreme demands on the muscles of the upper limbs. This would indicate that the force production may not be predominantly sourced from the small muscle groups of the shoulder and upper limbs. This appears to be corroborated by Baker *et al.* (1999) and Petrone *et al.* (2006) who investigated the actions of the trunk and Petrone *et al.* (2006) and Fleming *et al.* (2007) analysing motion of the legs during paddling. This indicates support for the coaching theories of Kemecsey (1986), which outline that despite the obvious importance of the upper body in the positioning and moving of the paddle, it is the trunk and the lower limbs that provide the paddler with the power and majority of the force that is imparted during the kayaking stroke, not the musculature of the shoulders and upper limbs. It is this insinuation made in coaching texts (Kemecsey, 1986; Kemecsey and Moll, 1998) that has been the focus of this doctoral thesis with the significant findings in trunk rotation, leg movement and leg extension identified in the notational analysis (Chapter 3) further reinforcing the proposed importance of the trunk and legs.

Therefore the entire technique will be analysed, however specific attention will be paid to the trunk and legs, using electromyography, electrogoniometery, kinetics and kinematics as investigative tools. The study has four main aims, these are:

i. Clarify the interaction between the movements of the upper body, trunk and the lower body;
ii. Establish if a significant relationship between force and boat velocity is apparent.
iii. Establish the link between the motions and muscular activation in the legs and trunk and how these relate to the average boat velocity throughout the kayak stroke;
iv. Establish the link between the motions and muscular activation of the legs and trunk and the forces produced at the paddle.

From the four main aims of the study a number of hypotheses were formulated:

Primary Hypothesis

Ha1: There will be a significant relationship between boat velocity and force production.

Ha2: There will be a significant relationship between boat velocity and the muscular activation of leg and trunk muscles.

Ha3: There will be a significant relationship between force production and the muscular activation of leg and trunk muscles.

Ha4: There will be a significant relationship between boat velocity and the joint angles of the body.

Ha5: There will be a significant relationship between force production and the joint angles of the body.

4.2. Method

4.2.1. Subjects

Testing was completed during two separate sessions following consent from the University of Chichester Ethics Committee. The initial session was completed at Dorney Lake, Eton in June 2006. The second testing session was completed at the National Water Sports Centre, Holme Pierrepont, Nottingham in June 2006. Both testing sessions were conducted in dry weather conditions with some light winds. Eight international level subjects 6 male (age 24 ± 4.8 years, height 1.81 ± 0.09 m, mass 82.6 ± 6.5 kg) and 2 female (age 26.5 ± 2.1 years, height 1.78 ± 0.08 m, mass 70.5 ± 3.5 kg), all injury free, completed the testing protocol after completing informed consent and medical questionnaires. Both male and female paddlers were included in this study, as no differences in technique have been highlighted in previous research for international standard athletes (Baker *et al.*, 1999). Baker *et al.*'s (1999) findings were reinforced by the research detailed in chapter 3 (Notational analysis of sprint kayaking technique).

4.3. Experimental Setup and Subject Preparation

4.3.1. Kinematics

Kinematic analysis incorporated the use of high-speed video cameras and digital video cameras. Two Peak Performance HSC-200PM cameras were positioned on tripods 15 metres apart, at 2.5m above water level, with an angle of approximately 100° between the camera lenses (figure 4.5). The cameras were linked through a Peak Performance Technologies Event and Video

Control synchronisation box, with the footage recorded on Fuji-Film SVHS video cassettes using Panasonic AG-MD830 SVHS video recorders. The 31 point floating calibration frame (see figure 4.6) was then floated into position between two buoys and anchored by a rope from the bank, and held in place to ensure the frame was still during the capture of the calibration footage. The frame was then removed and the calibrated space marked by the buoys. The subjects were informed of the calibrated area that they were required to paddle through.

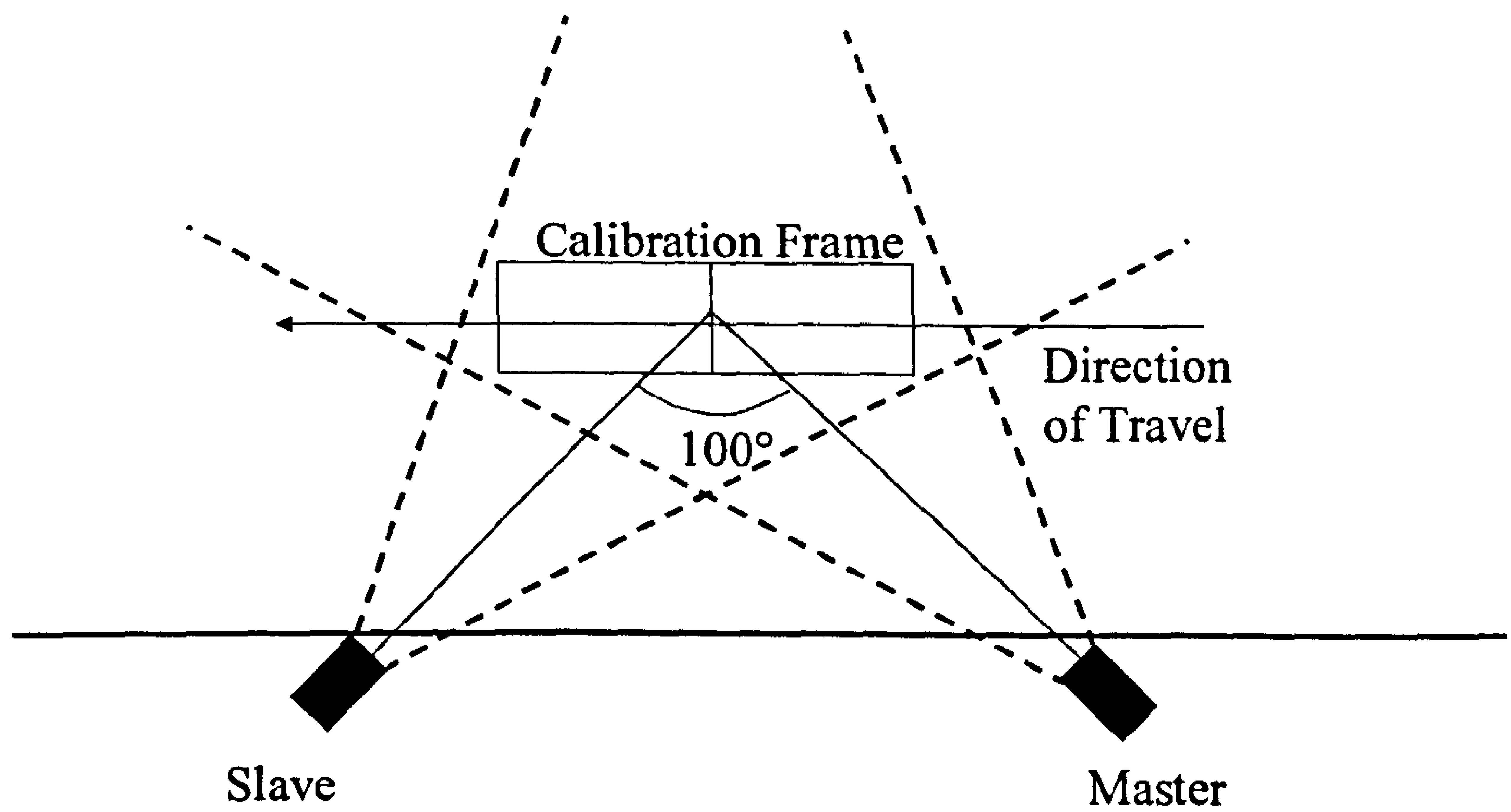


Figure 4.5. Schematic of high speed camera setup.

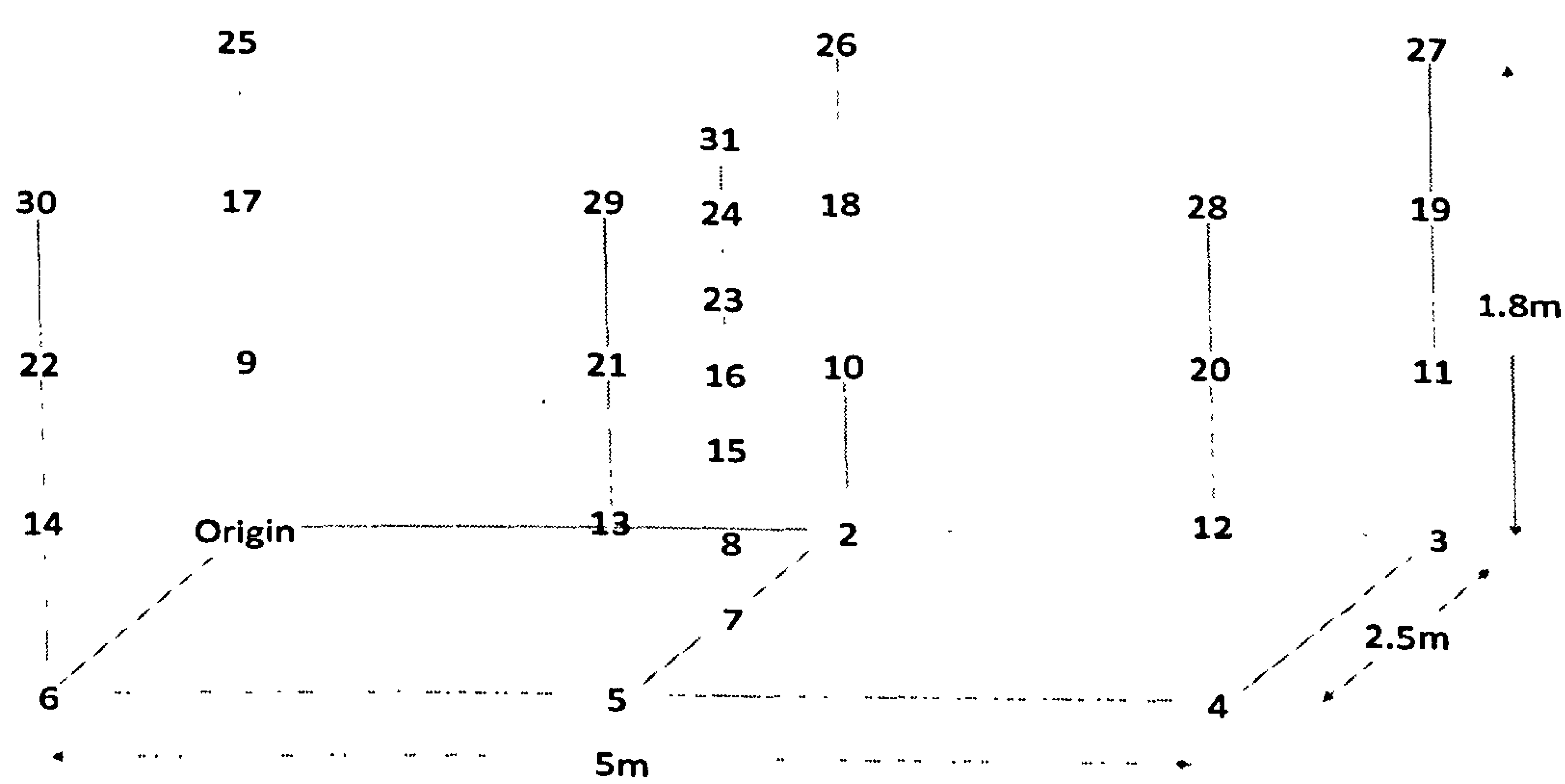


Figure 4.6. Schematic of the floating calibration frame

Subjects were marked using black circular elastoplast fabric markers 0.05 m in diameter with a white central circle of 0.01 m in diameter. These were positioned over the major joints of the upper body and knees using bony landmarks as defined below to determine the centre of the joint.

1. Right Wrist – marker positioned over the styloid process of the ulna;
2. Left Wrist – marker positioned over the styloid process of the ulna;
3. Right Elbow – marker positioned over the lateral epicondyle of the humerus;
4. Left Elbow – marker positioned over the lateral epicondyle of the humerus;
5. Right Shoulder – marker positioned on the lateral aspect of the upper arm level with the head of the humerus;
6. Left Shoulder – marker positioned on the lateral aspect of the upper arm level with the head of the humerus;
7. Right Trunk - a point measured 0.25 m above the greater trochanter, on a line between the centre of the hip and shoulder when standing in the anatomical position;
8. Left Trunk - a point measured 0.25 m above the greater trochanter, on a line between the centre of the hip and shoulder when standing in the anatomical position;
9. Right Knee – marker positioned over the lateral epicondyle of the femur;
10. Left Knee – marker positioned over the lateral epicondyle of the femur;

4.3.2. Electromyography

Mediotest Blue Sensor passive silver capsule surface electrodes, used in conjunction with MIE Medical Research Ltd 4K preamplifiers (3 – 250 Hz) were attached over the belly of the muscle at 0.05m intervals to record the activation of the major muscles of the trunk and lower limbs, more specifically, the External Obliques (figure 4.7), Rectus Abdominus (4.7), Gastrocnemius (figure 4.8), Biceps Femoris (figure 4.9), Rectus Femoris (Figure 4.10), and Latissimus Dorsi (figure 4.11) on the left and right side. The action of these muscles identified for the pilot study were detailed in table 3.1). The electrodes were placed (in line with the direction of the muscle fibres) over the muscle belly (4.7 to 4.11 depict the electrode placement). After electrode application the electrodes were monitored to ensure good quality EMG data acquisition using the MyoDat live feedback function.

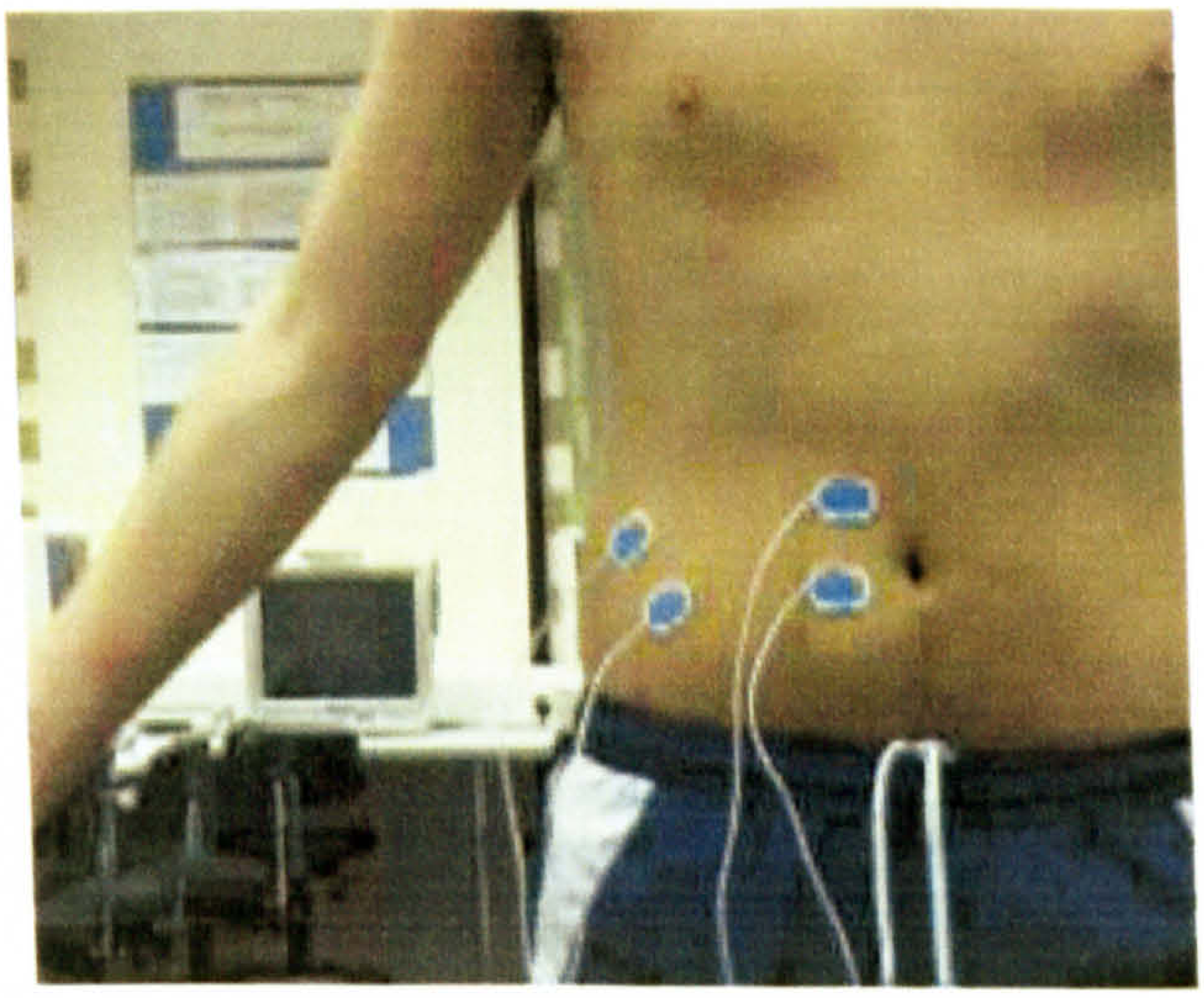


Figure 4.7. a. External Oblique electrode positioning (left).
b. Rectus Abdominus electrode placement (right).

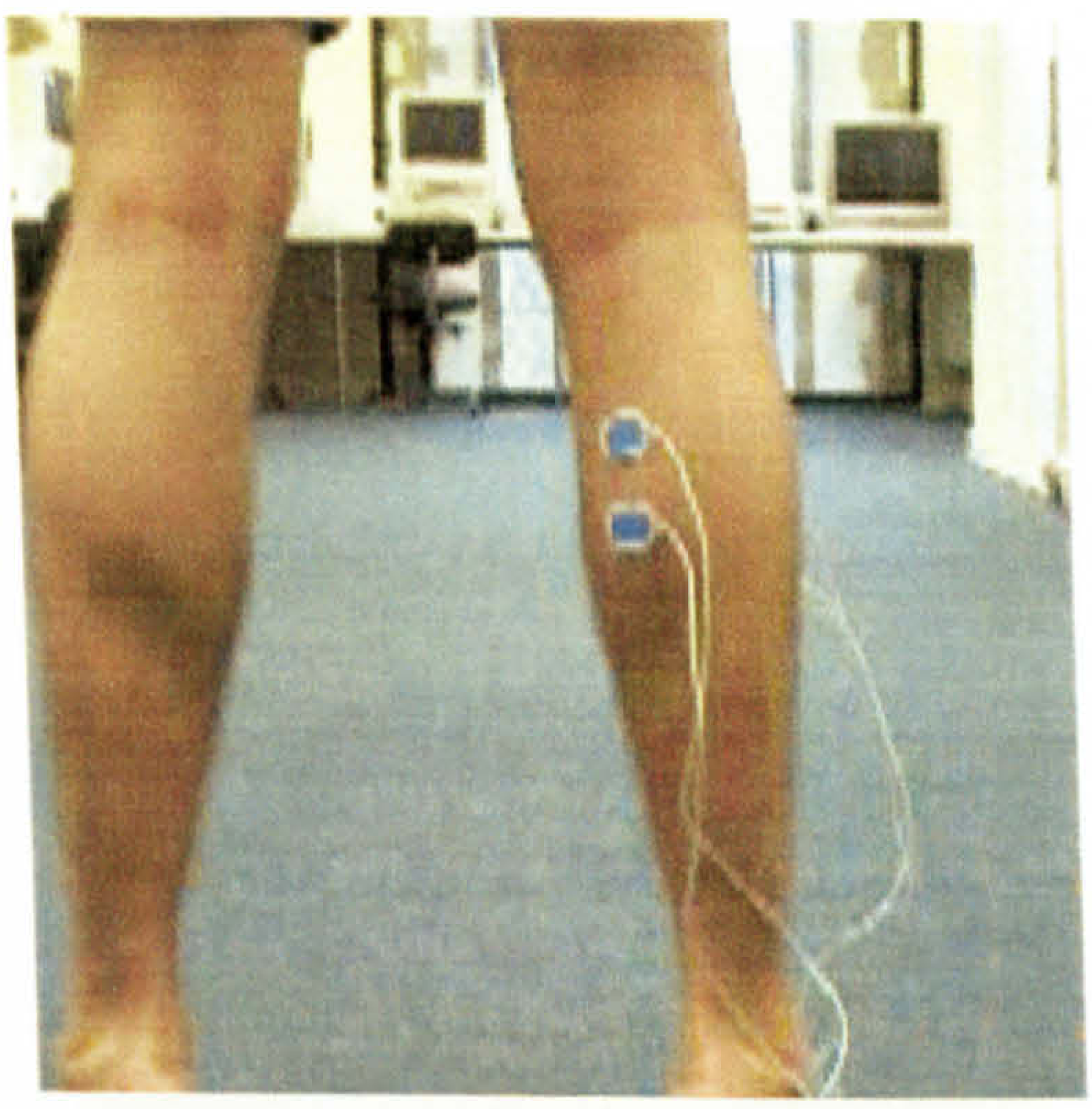


Figure 4.8. Gastrocnemius electrode placement (medial head).

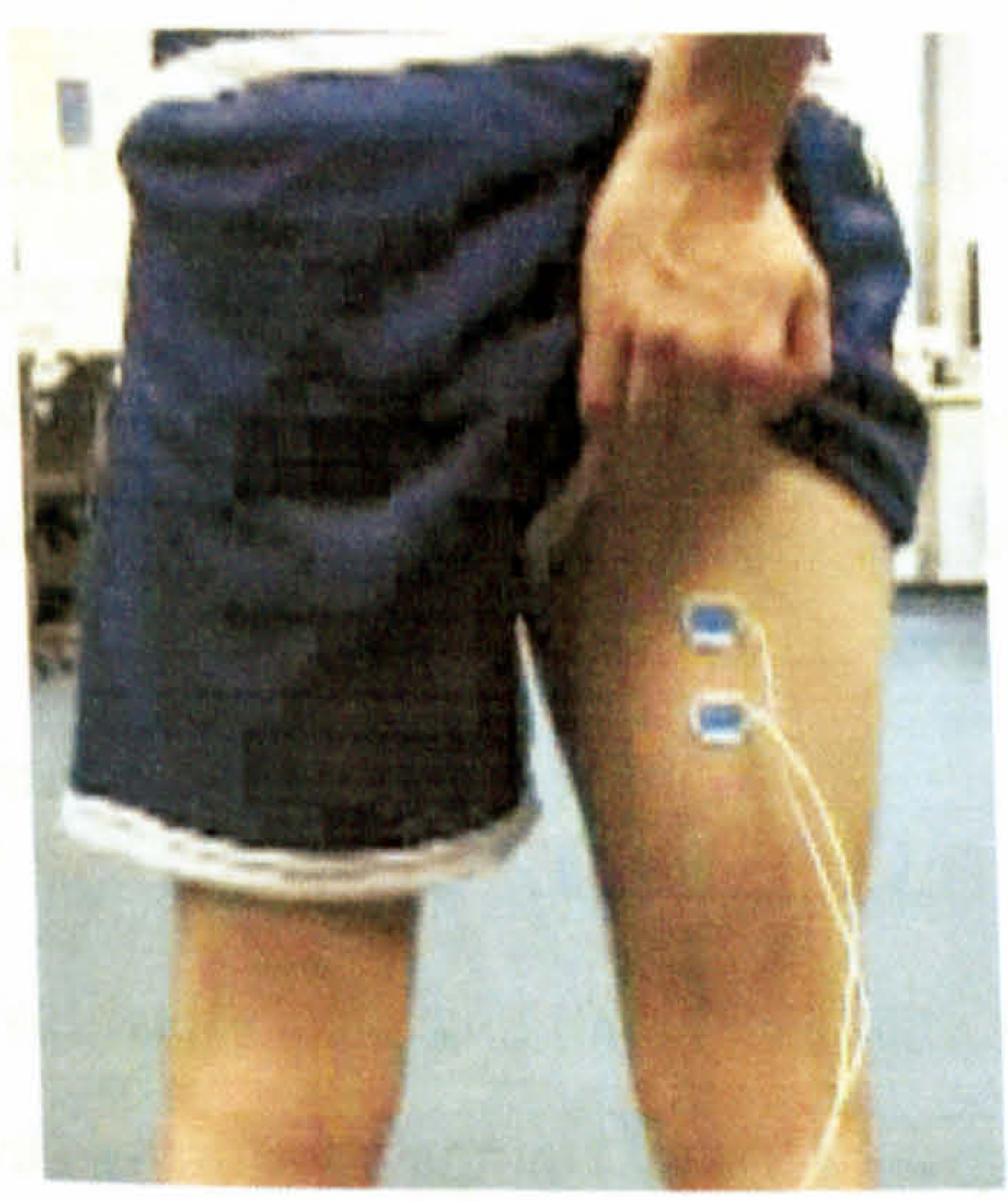


Figure 4.9. Biceps Femoris electrode placement on posterior of thigh.

Figure 4.10. Rectus Femoris electrode placement

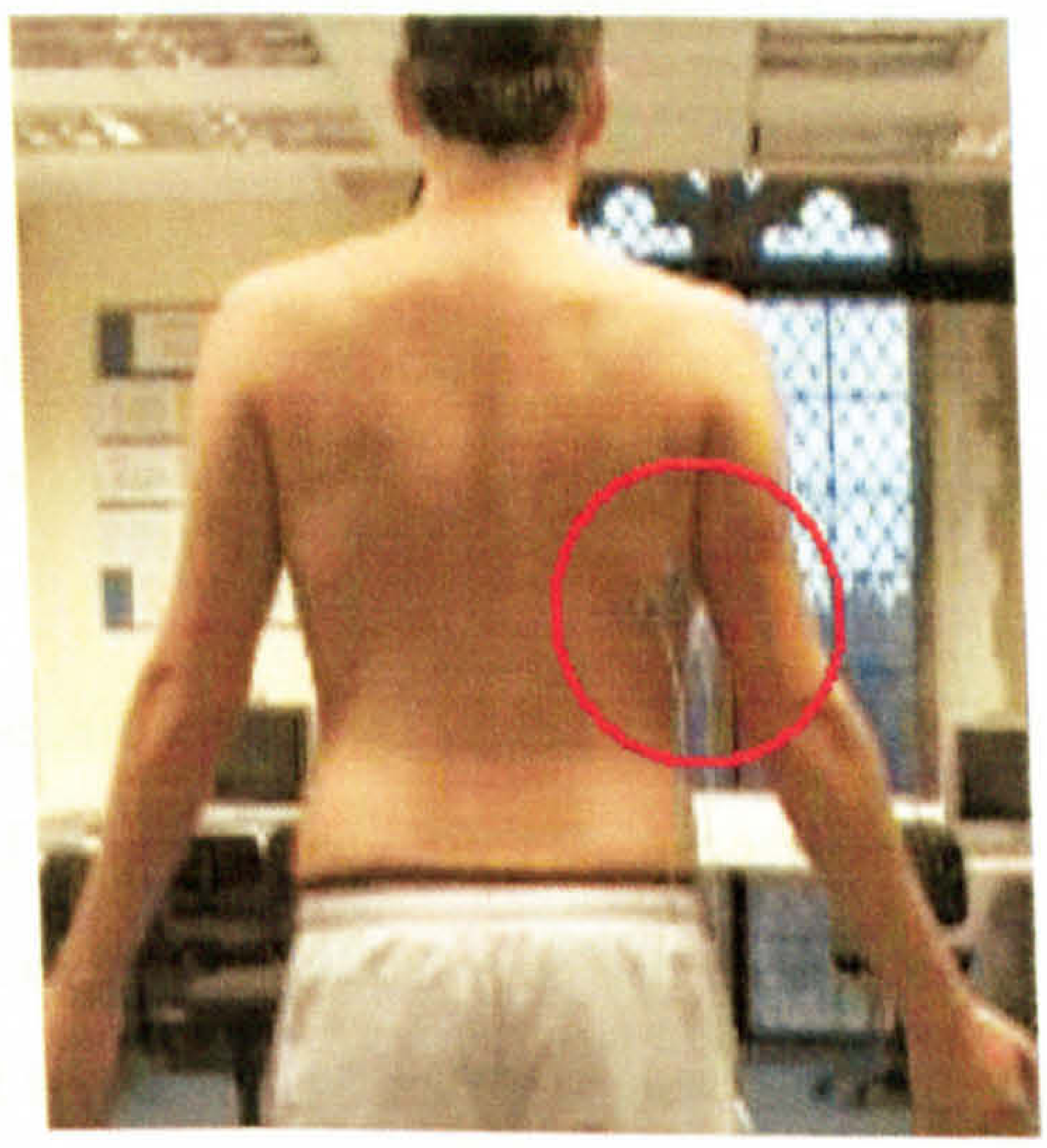


Figure 4.11. Latissimus Dorsi electrode placement

Following preparation the subjects were asked to generate a number of Maximal Voluntary Contractions (MVC). Each of the maximal efforts were produced against manual resistance (details of which follow) and were held for 5 seconds and repeated twice on the left and right side of the body. All MVC's were recorded at 500 Hz using the MIE Data Loggers.

4.3.2.1. Manual Resistance Procedures for MVC's

1. Rectus Femoris – the subject was seated on a chair with the hips and knees flexed to 90°. The chair back was positioned against a wall to stop any backward movement of the chair. An experimenter positioned themselves with their shoulder pressed against the shin of the subject. The subject was instructed to attempt to extend the knee.

2. Biceps Femoris – the subject was seated on a chair with the hip flexed at 90°. The subjects' feet were positioned on another chair opposite them, resulting in a neutral (fully extended) knee position. Pressure was them applied just superior and inferior to the knee, while the subject was asked to attempt to flex their knee.
3. Gastrocnemius – the subject was seated on a chair with the hips flexed at 90°. The calves were then rested on a chair with the knees fully extended with the feet hanging over the end of the chair. An experimenter positioned himself so that the subject was pushing against the shoulder with the toes.
4. External Obliques – the subject stood with their back against the wall whilst the experimenter applied resistance to the contralateral side to that of the movement. The subject was then asked to attempt to rotate and flex the trunk.

Each of the maximal voluntary contractions was carried out on both sides of the body alternately.

5. Rectus Abdominus – the subject stood with their back against the wall, an experimenter applied pressure to the shoulders, against which the subject was ask to produce a crunching motion.
6. Latissimus Dorsi – the subject stood with shoulders abducted at 90° from the anatomical position. Two experimenters then positioned themselves under the elbows of the subject while placing their hands over the shoulders of the subject. The subject was then asked to attempt to push their arm downward whilst the experimenter resisted the movement and kept the subject on the ground by pulling down on the subjects' shoulders.

4.3.3. Electrogoniometry

Biometrics SG150/W waterproof electrogoniometers were used to determine the angle at the left and right knees in addition to two Biometrics Ltd. Q150/W waterproof torsiometers that were used to measure the rotation of the trunk. The Biometrics Ltd SG150/W bi-planar sliding electrogoniometers (DC – to 250 Hz) were adapted for use with the MIE data Loggers which were programmed to sample at 500 Hz.

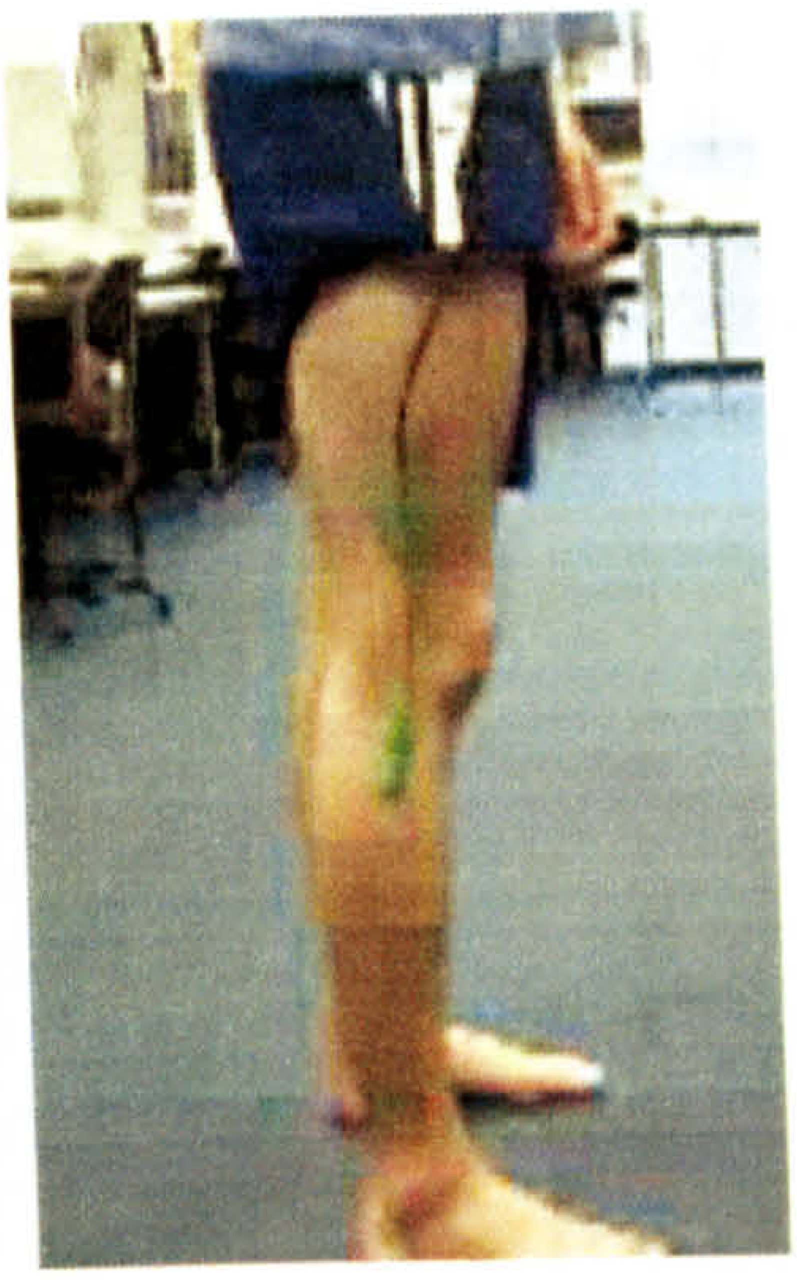


Figure 4.12. Electrogoniometer placement for the knee joint.

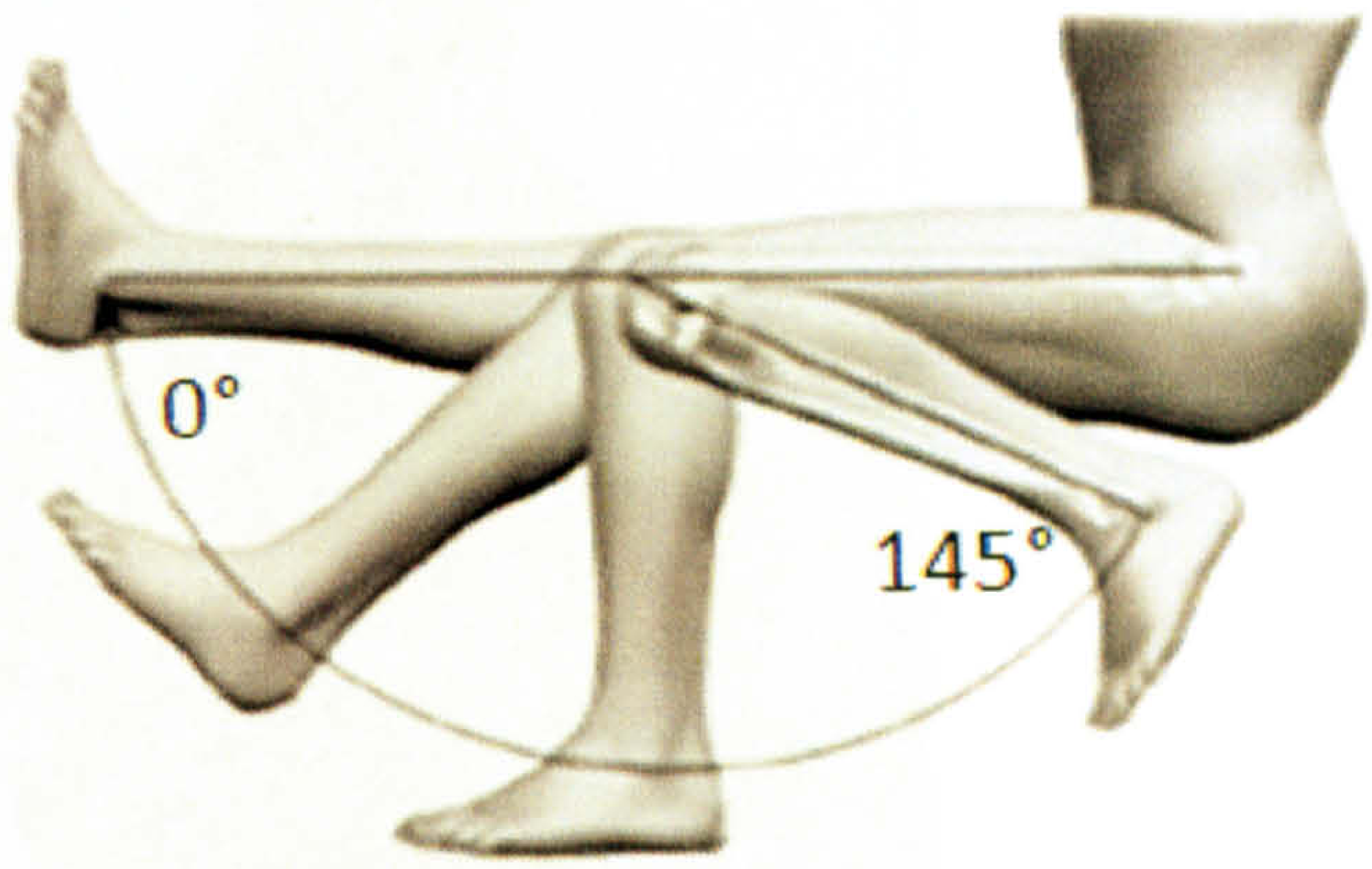


Figure 4.13. Orientation of knee angle measurement. (adapted from http://www.zimmer.co.za/z/ctl/op/global/action/1/id/520/template/PC/navid/2129, 27-10-2008)

A single electrogoniometer was positioned over each knee (figure 4.12) with the fixed end attached to the lateral aspect of the thigh parallel to the Femur with the sliding end attached to the lateral surface of the calf running parallel to the tibia. Electrogoniometers were unsuitable for the measurement of the hip angle as detailed in chapter 4. In a response to this a reference marker was placed 0.25 m superior to the greater trochanter of the femur on both the left and right sides of the trunk. The knee angle was determined as the change in the knee angle from a neutral position as depicted in figure 4.13.

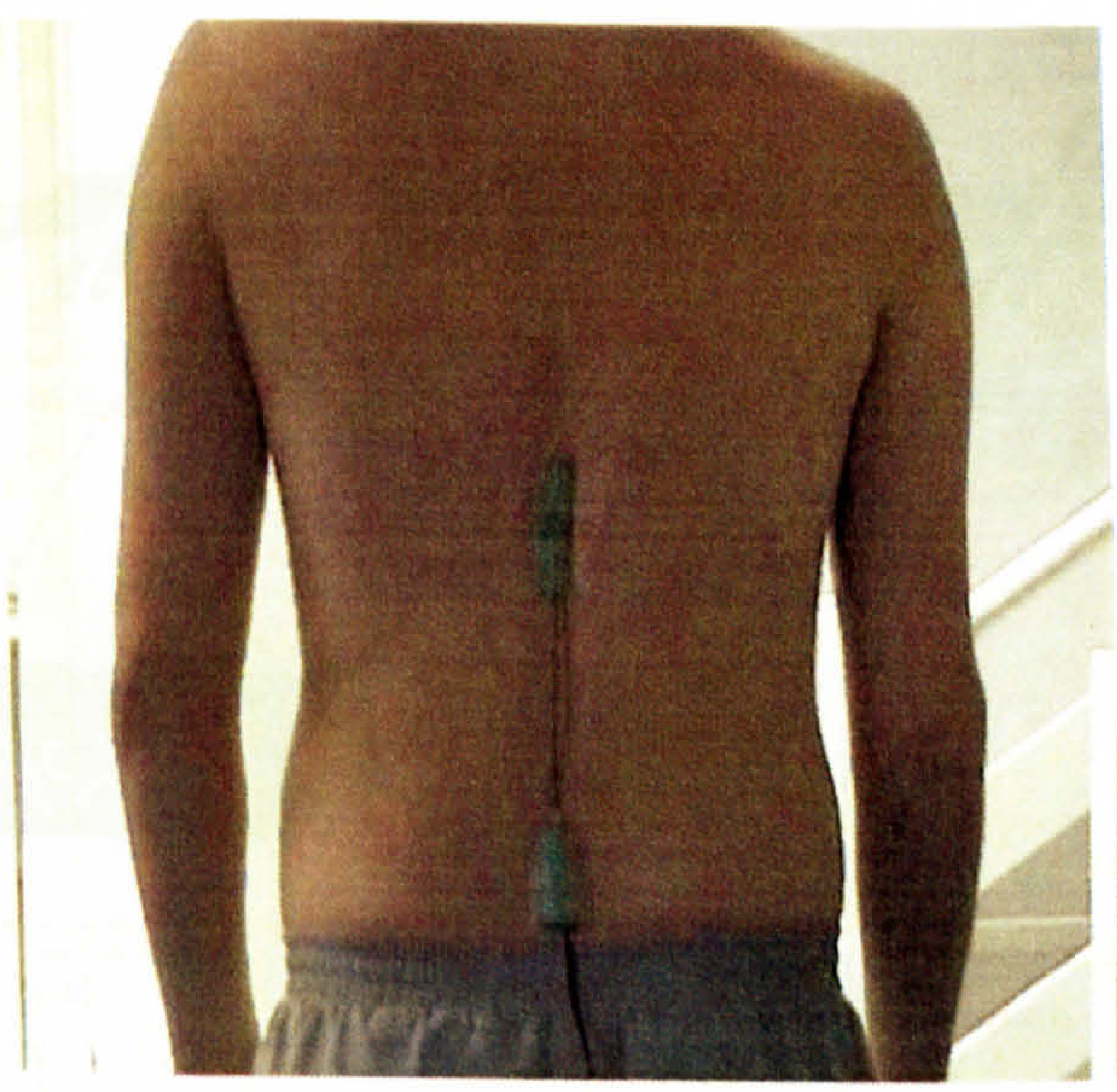


Figure 4.14. Lumbar torsiometer placement.

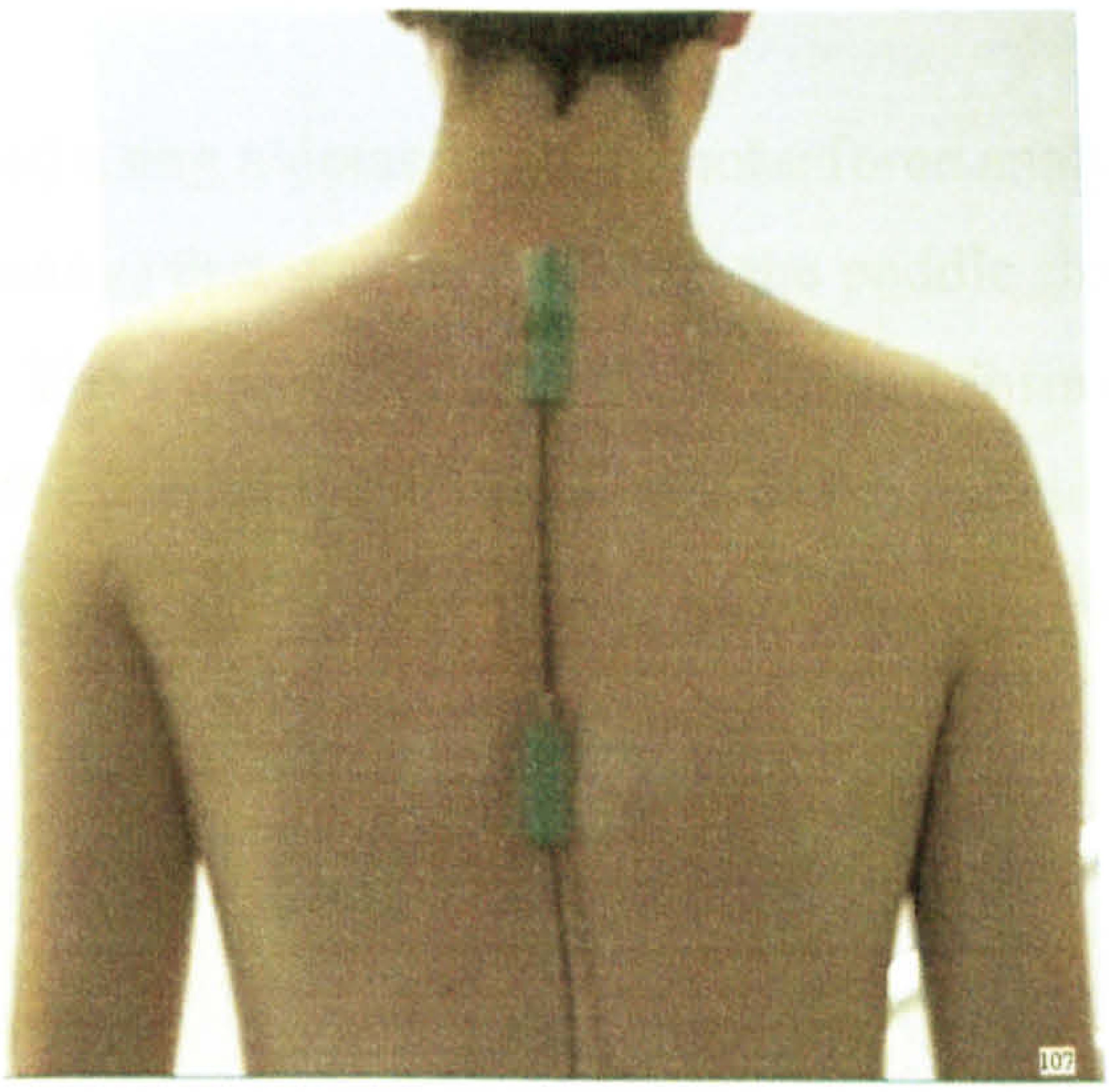


Figure 4.15. Thoracic torsiometer placement.

The torsiometers were positioned over the lumbar and lower thoracic vertebrae and then the upper thoracic vertebrae. The torsiometers ran across the surface of the skin over the spinaeous processes of the vertebrae, with the fixed end proximal to the base of the spinal column. The lumbar torsiometer ran from lumbar 5 up to thoracic 10 or 11 dependent on the length of the subjects' spinal column (see Figure 4.14). The thoracic torsiometer ran from thoracic 9 upwards ending around thoracic 1 or cervical 7, again dependent on the subject (see figure 4.15).

4.3.4. Kinetic Analysis

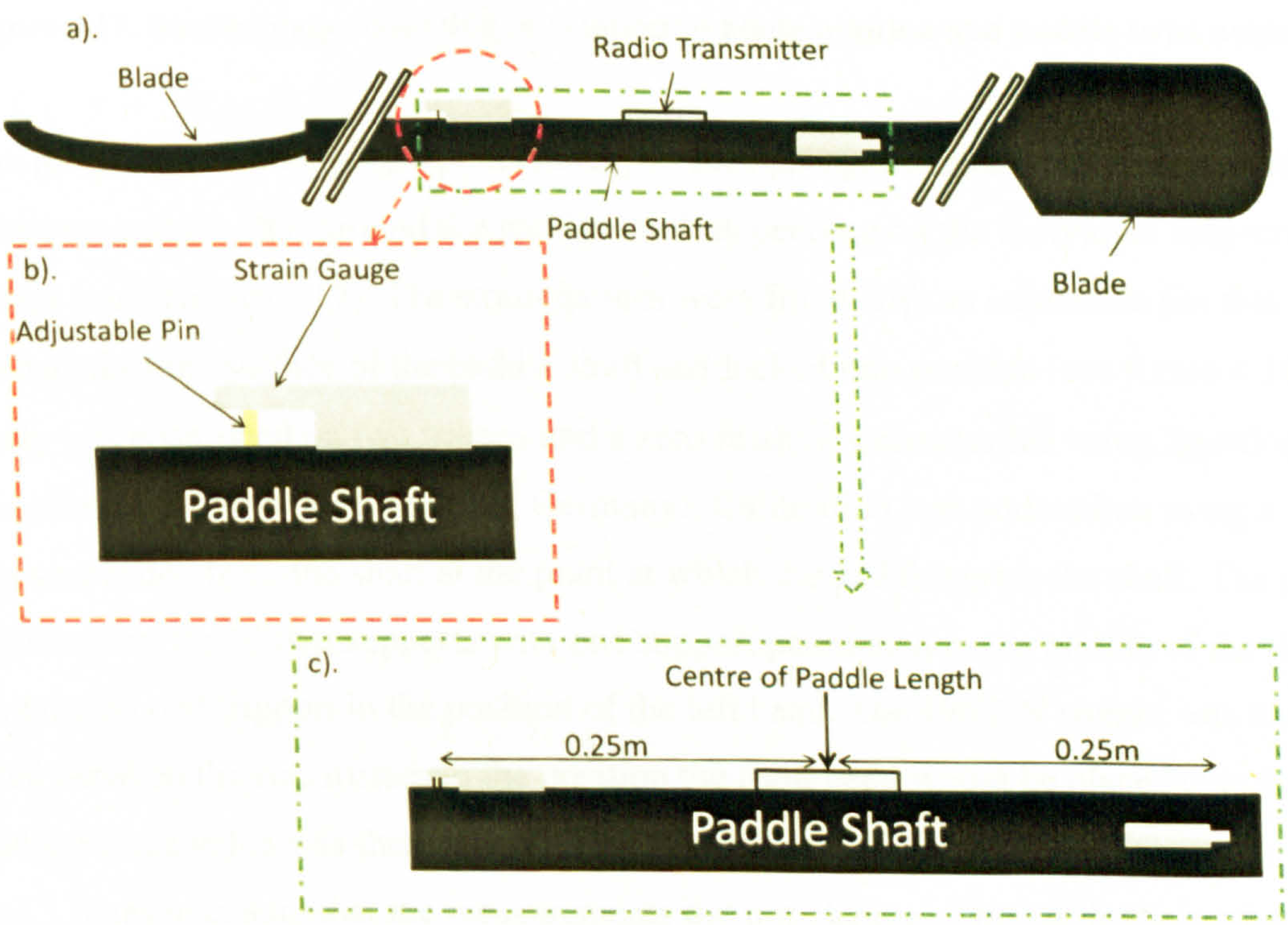


Figure 4.16. Paddle force analysis system.

Kinetic analysis was produced using a detachable bespoke force analysis system developed by Sperlich and Sperlich, (Germany) that was mounted on the paddle shaft, allowing subjects to use their individual paddles. The system comprised of a radio transmitter and two strain gauges were mounted on the shaft, the transmitter in the centre of the paddle shaft, with a strain gauge positioned 0.25 m in either direction from the transmitter (figure 4.16/c).

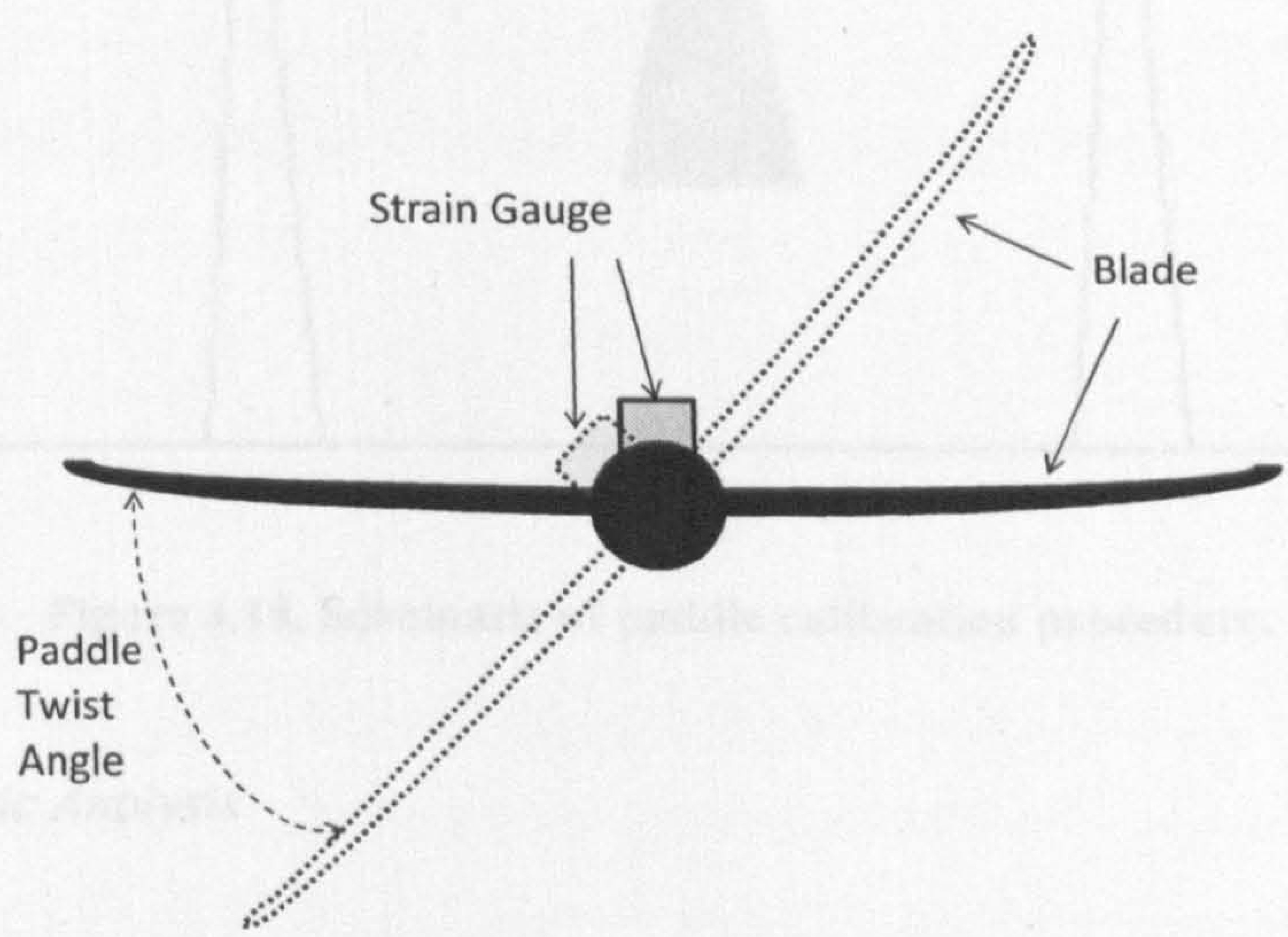


Figure 4.17. Strain gauge mounting in relation to blade position and paddle twist angle.

The strain gauges were mounted perpendicularly to the appropriate blade, out of phase from one another by between 60 - 85° around the paddle shaft, depending on the individual subjects paddle twist angle (figure 4.17). The strain gauges were fitted with an adjustable pin that is positioned against the surface of the paddle shaft and locked into position (see figure 4.16/b). The paddle was positioned on two trusses and a zero reading was recorded using Sportlogger analysis software (Sperlich and Sperlich, Germany). Calibration was undertaken using a 196.2 N weight suspended from the shaft at the point at which the paddler grips the shaft. The paddle was positioned on top of two supports with one support positioned in the middle of the right blade and the second support in the position of the left hand. The 196.2 N weight was then suspended between the two trusses in the position the right hand would be placed (see figure 4.18) and the force value was then entered into the software. The weight was then removed and reapplied 5 times to ensure that the measurements did not change. This calibration process was then repeated on the left end of the paddle to ensure both ends of the shaft were calibrated as the structure of the shaft material may not have been uniform. This process was completed for each paddlers' paddle, minimising variation due to hand positioning and paddle twist/blade offset. Data was collected at 500Hz and recorded using Sportlogger analysis software (Sperlich and Sperlich, Germany).

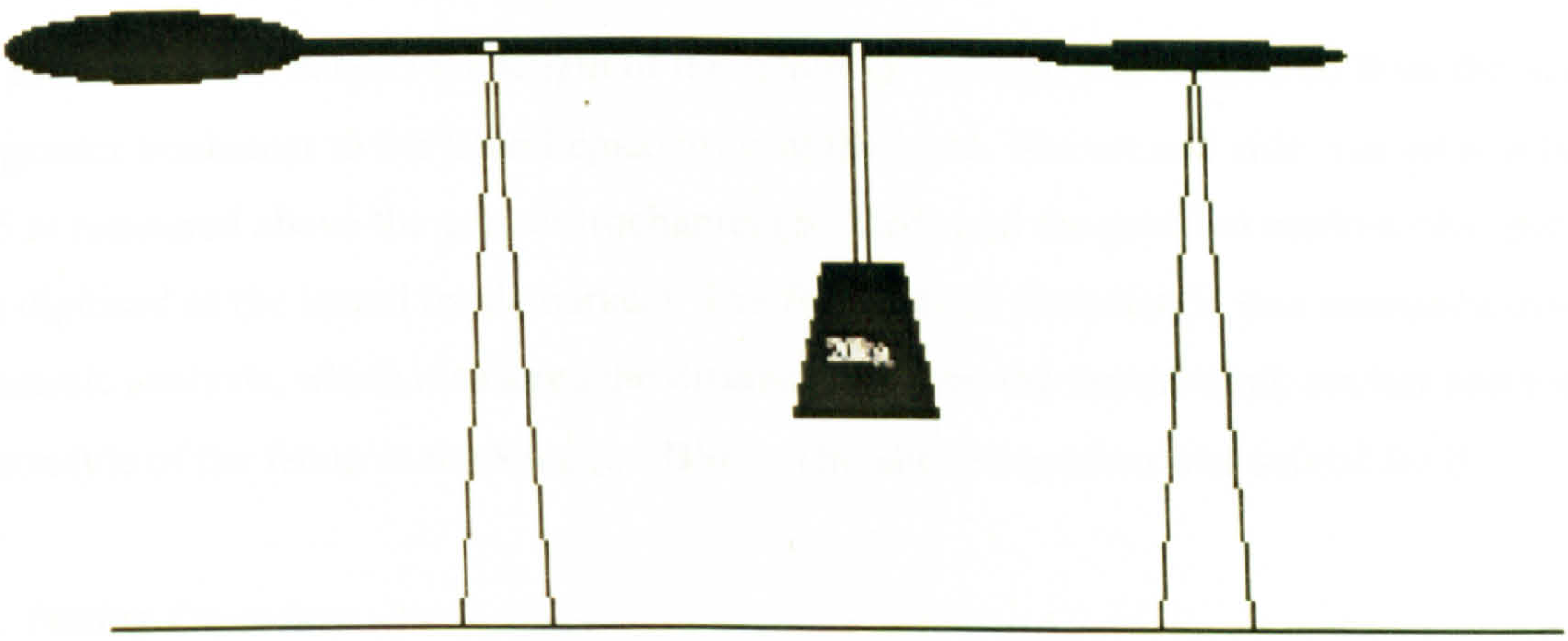


Figure 4.18. Schematic of paddle calibration procedure.

4.3.5. Trigonometric Analysis

Trigonometry was used in determining the angle of the hip (dotted pink line), as pilot testing had determined that the use of electrogoniometers or kinematic analysis was unfeasible. The law of cosines was applied as the triangle, the points made up of the greater trochanter, a designated point 0.25 m above the greater trochanter and the lateral epicondyle of the femur at the knee, was an oblique triangle (see figure 4.19).

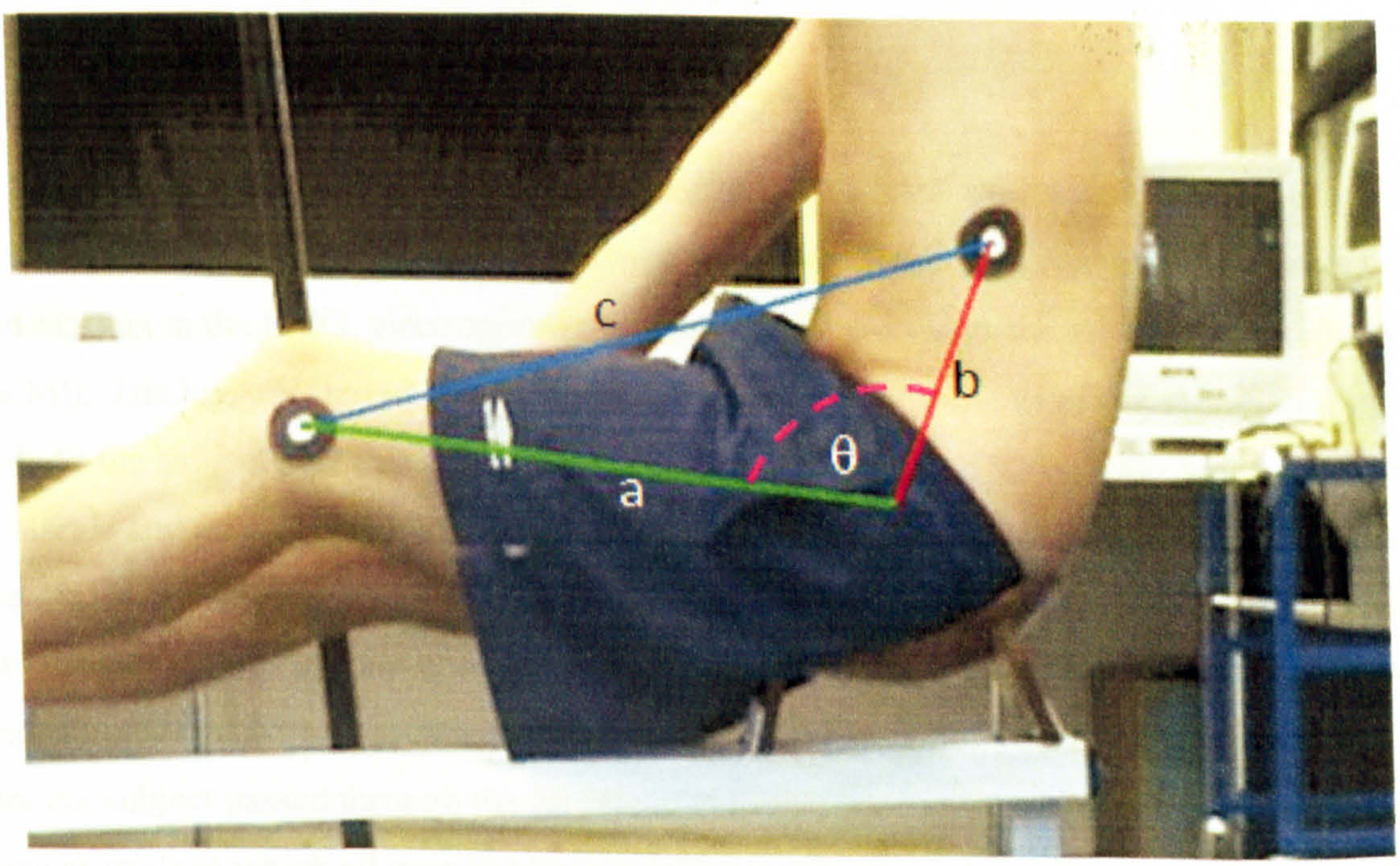


Figure 4.19. Marker set for hip angle determination.

The law of cosines states that:

$$c^2 = a^2 + b^2 - 2ab \cos C$$

For each individual subject the length of the femur (a - Green) was measured from the head of the greater trochanter to the lateral epicondyle at the knee. The second side was set at a standard 0.25 m measured above the greater trochanter (b - Red) and the position marked (this position was digitised as the lateral trunk marker). The final side of the triangle was measured using the kinematic analysis, which measured the distance between the lateral trunk marker and the lateral epicondyle of the femur at the knee (c - Blue). The above equation was solved for θ.

4.4. Testing Procedure

Following preparation the subjects were provided a 10 minute acclimatisation period. This served several purposes, initially allowing the paddler to warm up and get used to paddling with the recording equipment. Secondly to become familiar with the operation of the minidisc data collection module used with the kinetic analysis system and finally to ensure that no sensors worked loose during paddling. Following the acclimatisation period the subjects were instructed to complete a 75 m sprint trial over which they were to paddle at maximal velocity, consisting of a 50 m acceleration phase, through a 5 m pre-calibrated volume, designated by buoys and then a run off length 20 m. It was further emphasised that the subjects should maintain maximum velocity through to the end of the run off to ensure that there was no reduction in velocity through the calibrated volume.

Prior to each trial the subject activated the telemetry for the force analysis system on the paddle shaft and then held a still position. This allowed easy identification of each trial as it produced a period of quiet in the EMG, electrogoniometer and torsiometer data traces. This was important as the MIE data loggers started collecting data at 500 Hz from the start of the acclimatisation period. As the subject held this still position the Panasonic AG-MD830 SVHS video recorders were started and a Sony Handycam DCR-PC53E digital video camera, positioned 2.5 metres above the water capturing footage at 50 Hz, was started and panned throughout the trials to ensure the subject was in frame for the entire trial. After completion of the trial all systems with the exception of the MIE data loggers were switched off and video footage was reviewed to ensure the subject passed through the middle of the calibrated volume. Acceptable trials were defined as trials in which all measurement systems were active, the subject passed through the centre of the calibrated volume and the subject did not reduce velocity within the calibrated volume. This was carried out until each subject completed 5 trials and each had been captured.

4.5. Data Preparation, Synchronisation, Reduction and Analysis

4.5.1 Data Preparation

4.5.1.1. Kinematics

Footage collected during the testing sessions was digitised using Motus 32 motion analysis software producing a 3-dimensional reproduction of technique using the direct linear transformation (DLT) method (Abdel-Aziz and Karara, 1971). Reconstruction accuracy within the calibrated area was determined to have a resultant error of no greater than 0.4 ± 0.01% across all trials, which was determined to be acceptable (appendix F for accuracies). Three dimensional reconstruction of the subjects used a 17 point partial body spatial model (figure 4.20) with anatomical landmarks, positions on the paddle and locations on the kayak, outlined below.

1. Right Wrist – marker positioned over the styloid process of the ulna;
2. Left Wrist – marker positioned over the styloid process of the ulna;
3. Right Elbow – marker positioned over the lateral epicondyle of the humerus;
4. Left Elbow – marker positioned over the lateral epicondyle of the humerus;
5. Right Shoulder – marker positioned on the lateral aspect of the upper arm level with the head of the humerus;
6. Left Shoulder – marker positioned on the lateral aspect of the upper arm level with the head of the humerus;
7. Right Trunk - a point measured 0.25 m above the greater trochanter, on a line between the centre of the hip and shoulder when standing in the anatomical position;
8. Left Trunk - a point measured 0.25 m above the greater trochanter, on a line between the centre of the hip and shoulder when standing in the anatomical position;
9. Right Knee – marker positioned over the lateral epicondyle of the femur;
10. Left Knee – marker positioned over the lateral epicondyle of the femur;
11. Right Blade - connection between paddle shaft and blade;
12. Left Blade - connection between paddle shaft and blade;
13. Right Hand second medial knuckle;

14. Left Hand second medial knuckle;
15. Head – a point judged to be the centre between the ears;
16. Stern;
17. Bow.

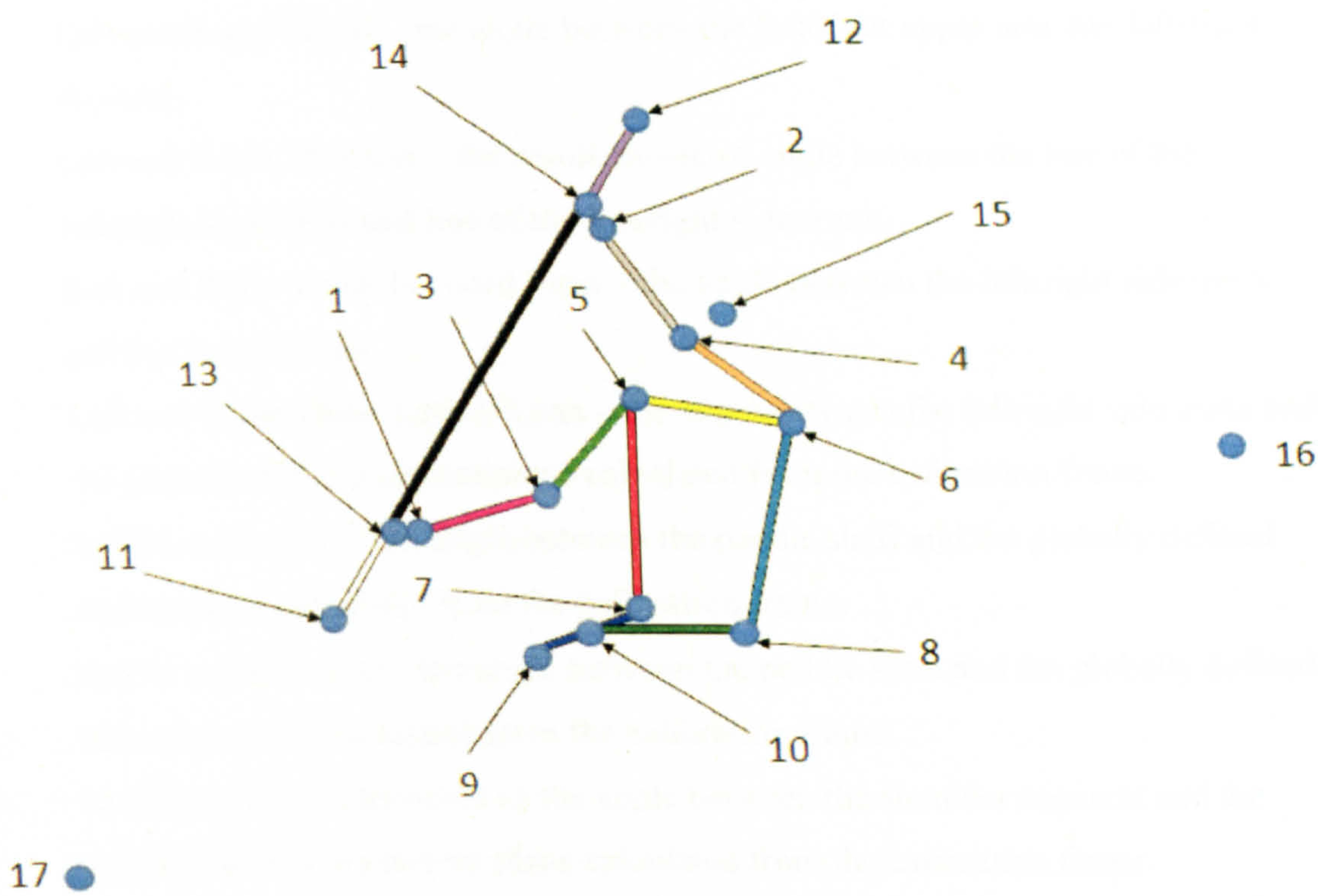


Figure 4.20. Three dimensional model utilised for kinematic analysis.

The digitised markers were used to define all body segments as follows:

i. Left Forearm – Line between left wrist and left elbow (grey);
ii. Right Forearm – Line between right wrist and right elbow (pink);
iii. Left Upper Arm – Line between left elbow and left shoulder (orange);
iv. Right Upper Arm – Line between right elbow and right shoulder (light green);
v. Shoulders – Line between right shoulder and left shoulder (yellow);
vi. Left Side Trunk – Line between left shoulder and left lateral trunk marker (turquoise);
vii. Right Side Trunk – Line between right shoulder and right lateral trunk marker (red);
viii. Paddle Shaft – Line between left and right hand (black);
ix. Left Blade – Line between left hand and left blade joint (purple);
x. Right Blade – Line between right hand and right blade joint (white);
xi. Left Hip definition line – line between left knee and left trunk marker (dark green);

xii. Right Hip definition line – line between right knee and right trunk marker (dark blue).

From the 3 dimensional model a number of body and paddle angles were determined as followed:

i. Left and Right Elbow – the angle between the left/right upper arm and left/right forearm.
ii. Left and Right Shoulder – the resultant/vector angle between the line of the left/right upper arm and line of the left/right side trunk.
iii. Left and Right Trunk Forward Lean – the angle between the left/right side trunk and the frontal plane.
iv. Left and Right Trunk Lateral Lean – the angle between the left/right side trunk and the globally defined sagittal plane calculated from the calibration frame.
v. Paddle to Vertical – the angle between the paddle shaft and the globally defined sagittal plane calculated from the calibration frame.
vi. Paddle to Horizontal – the angle between the paddle shaft and the globally defined transverse plane calculated from the calibration frame.
vii. Shoulder Tilt – Determined as the angle between the shoulder segment and the globally defined transverse plane calculated from the calibration frame.

From the reconstructed 17 point partial body model joint angles (including maximum, minimum and range), lengths between markers and boat velocity were derived. The raw data was conditioned using a fourth order Butterworth filter set at a 6 Hz cut off to smooth the data. Average boat velocity was determined from the x component of the head marker. A sixth order polynomial line of best fit was placed over the data trace to reduce the effects of forward and backward head movement. This was done to ensure the velocity of the head matched the velocity of the boat as closely as possible. The x component of the head was selected since the bow and stern markers proved unreliable because the stern submerged intermittently and the bow was not in frame, simultaneously with the paddler, long enough to extract sufficient data for analysis. Secondly the peak of the cockpit was lost from view during parts of the stroke from both angles, and from the master view was obscured by the subject as the paddler passed the mid frame point. Therefore using a sixth order polynomial on the x component of the head marker to derive boat velocity was the protocol that proved best, allowing the development of sufficient data to complete an analysis of paddling technique. The use of a sixth order polynomial line of best fit resulted in the removal of the majority of excess forward and backward head motion, whilst vertical and lateral head movement was excluded by the use of the x component.

The footage from the Sony Handycam DCR-PC53E digital video camera was reviewed and the number of strokes for each trial were calculated. Furthermore the strokes that occurred during the calibrated volume were identified for synchronisation between the various analysis systems.

4.5.1.2 Electromyography

Following acquisition data were downloaded into Myodat version 6.47 analysis software, on a Research Machines Plc. Intel Mobile Pentium 4 2.2 GHz Laptop. After downloading the traces were examined for noise that may have occurred once the subject was on-water. Any channels exhibiting excessive noise patterns were investigated further by determining if the noise saturated the signal. If there was excessive saturation, determined as greater than 10%, the trace was excluded from the final analysis. Following the inspection of the EMG traces were conditioned using a root mean squared linear envelope. Maximum voluntary contractions (MVC) values were calculated from the highest average over a second. From the conditioned traces the individual trials were identified and five second samples were extracted with the exact strokes that coincided with the subject passing through the calibrated volume at the mid-point of the data sample. These samples were entered into Microsoft Excel 2003 for synchronisation and further analysis. From the EMG data, peak muscular activation was extracted and reading from 0.01 seconds time points pre and post peak velocity and force were extracted for analysis.

4.5.1.3. Electrogoniometery

Following testing the dataloggers were downloaded into Myodat version 6.47 analysis software, on a Research Machines Plc. Intel Mobile Pentium 4 2.2 GHz Laptop. Trace inspection was conducted to identify any traces in which the electrogoniometers or torsiometers may have detached, identified by erroneous readings or noise. The exact strokes coinciding with the calibrated volume were identified from the stroke counting and extracted as part of a five second sample. These samples were entered into Microsoft Excel 2003 for synchronisation and further analysis. From the data maximum and minimum angles of rotation were recorded and the range of motion was determined.

4.5.1.4. *Kinetics*

After collection, data was downloaded into Sportlogger analysis software (Sperlich and Sperlich, Germany). Initially visual inspection was conducted to identify any noise or data spikes that can occur when the paddle of blade knocks against the kayak shell. These spikes were corrected by extracting the erroneous data points and replacing with a straight line. The smoothing was rarely conducted as the elite level athletes used only contacted the hull of the kayak with the blade on very few occasions. Strokes coinciding with the calibrated volume were then identified and a five second sample extracted and entered into Microsoft Excel 2003 for synchronisation and further analysis. From these force traces the total stroke impuse, peak force, mean force, time to peak force and time from peak force to paddle exit were determined.

4.5.2. Data Reduction and Synchronisation

The raw data collected was in excess of what was required for the technique analysis, therefore it was necessary for the data to be reduced allowing a more manageable size. Initially a basic synchronisation was conducted using stroke counting from the Sony Handycam DCR-PC53E digital video camera footage. This identified the stroke cycles from the EMG, electrogoniometer, torsiometer and force data traces that occurred within the calibrated volume. Five second samples, including the data occurring within the calibrated volume, were extracted from data traces for further synchronisation and analysis.

Detailed synchronisation between the kinematic and datalogger systems was conducted using the trace from the latissimus dorsi and high-speed video footage. The frame in which the blade of the paddle starts its backward sweep of the stroke must be caused by an extension of the shoulder, due to the locked elbow position. This extension will be caused by a contraction of the latissimus dorsi alongside other small shoulder muscles, therefore the initiation of activation was used to synchronise the various systems. The synchronisation point was identified as the point at which a 5% increase in the activation from the lowest level just prior to the initiation of the climb to peak activation. The latissimus dorsi was selected for synchronisation as Logan and Holt (1985) identified this synchronisation during their investigation into on-ergometer paddling technique, this was corroborated by Fleming *et al.* (2007).

Synchronisation with the force analysis system was conducted using the point of paddle entry from the high speed kinematic footage and the point at which a threshold of 15 N was achieved in the force signal, as based on guidance from the Sports Science Officer of the British Canoe Union. The varying sample rates of the high-speed video (200 Hz), force analysis system (500 Hz) and the data logger system used for the EMG and electrogoniometry analysis (500 Hz) were compensated for by transforming data sets into 1000 Hz using Microsoft Excel 2003 by insertion of rows between data points, resulting in an accuracy within 0.005 - 0.01 of a second, which was deemed acceptable.

Following synchronisation all data sets were normalised, EMG traces to MVC's and all force, torsiometer and electrogoniometer traces to the pre recorded baselines. Graphical representations of the data traces were then produced defining individual left and right sided strokes for an initial visual analysis. Visual inspection identified that the majority of the muscular activity occurred during contact between the water and paddle. This finding in conjunction with the indications of previous research that the 'air work' has no contribution to the forward propulsion of the kayak (Plagenhoef, 1979; Mann and Kearney, 1980) resulted in the statistical analysis of the technique focusing on the actions and activations during the time the paddle is in contact with the water. Furthermore visual inspection identified that the peak intra stroke force development occurred midway through the stroke, with the peak intra stroke velocity peaking toward the end of the stroke and the majority of the muscular activity occurred before both intra stroke force and velocity peaked. Consequently it was decided to focus on the data in the 0.25 seconds prior to peak velocity and 0.1seconds after, as this time frame also covered the effective time the paddle was in contact with the water. As the force and velocity peaks did not coincide the same method was employed when analysing the measured variables relationships with force.

The intra stroke peak velocity and peak force for the left and right sided strokes falling within the calibrated volume were extracted along with the values from all measured variables at this time point. In addition to the values coinciding with peak velocity/force, data was extracted from all data series every 0.01 seconds in the 0.25 seconds prior to peak and 0.1 seconds following. This process was repeated for all trials, from which average data was calculated for each individual subject. This was required as not all subject trials were found to be acceptable when brought to analysis due to changing light conditions during the trials. Furthermore it should be noted that the number of left and right sided strokes were not uniform over all subjects, therefore reinforcing the requirement of averaged data for each subject to be used for the statistical analysis.

In addition to force and velocity peaks, the mean velocity throughout the trial was determined and mean force from each stroke was determined. Furthermore the total stroke impulse produced over the stroke was calculated, and the time taken to reach peak force and the time from the occurrence of peak force to paddle exit measured. Moreover peak levels of muscular activation were recorded for each muscle during both left and right paddle strokes to investigate their influence on the velocity and force attained by the paddlers. Finally maximal, minimal and range data was derived for all joint angles for each subject to examine if their orientation had a significant relationship with the velocity or force production. From the mean values calculated for each subject, overall population averages were determined for the pool of subjects.

4.6 Statistical and Technique Analysis

The mean kayak velocity a paddler can attain will ultimately determine their finishing position during competition and will therefore be treated as the primary dependent variable within the current research, with peak intra stroke velocity acting as the secondary dependant variable. The mean and peak velocities a paddler can achieve have been suggested to be directly linked to the propulsive forces the paddler generates dependent upon the direction of application of the force (Plagenhoef, 1979, Mann and Kearney 1980, Marhold and Herrmann, 1989; Robinson *et al.* 2002), therefore mean and peak paddle force production will be utilised as the third and fourth dependent variables.

Initially investigation focused upon the ideal technique outlined by Kemecsey (1986), which expressed a symmetrical technique. This was conducted through the utilisation of the data traces recorded to ascertain the accuracy of the technique and identify any asymmetry during paddling technique. Furthermore investigation of the asymmetry during technique was investigated through empirical methods, using SPSS version 16.0 to compare group means using independent sample t-tests on the force and velocity measures.

To understand how the contractions of the muscles in the legs and trunk (along with the positioning of the limbs) affect the mean and peak intra stroke boat velocity and mean and peak force production, the data sets were split by time point and side and a series of normality tests were conducted. Acceptable levels of normal distribution were determined considering the skewness and kurtosis of the data relative to the standard errors of skewness and kurtosis respectively. From this calculation any values outside of -1.96 and 1.96 were deemed to be outside acceptable levels. Data sets outside acceptable limits were transformed using a Log 10 transformation on variables exhibiting positive skewness and reflected Log 10 transformation algorithms for negatively skewed data sets (Tabachnick and Fidell, 1996; Betts *et al.* 2006; Oaten *et al.* 2008).

Once normal distribution was determined and transformation conducted, t-tests were used to investigate asymmetry in the force, velocity and time variables between the left and right paddle strokes. Pearsons correlations and a series of simple linear regressions were used to determine relationships between boat velocity, force production and the measured variables. Ideally a multiple regression analysis would have been conducted to identify the combination of variables that contribute to the mean boat velocity. Simple linear regression analysis was chosen, as Field (2005) proposes that for a multiple regression analysis a minimum of 10 subjects for each independent variable. The number of sprint kayaking podium level athletes within the Great Britain squad is limited to 10-12 paddlers, whilst 47 independent variables were measured in this research meaning a multiple regression analysis was unsuitable to apply to the data. Simple regression analysis was therefore selected to determine significant relationships between the velocity and force (dependent) variables and the muscular activities, joint angles, and joint centre velocities.

In addition to the simple regressions used to analyse the mean and peak values derived from acquired EMG data, an indication to the sequencing of the muscular activity was investigated also. This was deemed important as in other types of cyclical locomotion muscular activation sequencing patterns are key to performance (Mangold *et al.* 2001). Visual inspection was used to identify general trends exhibited across subjects and draw comparisons with the teachings of coaching texts (Kemecsey, 1986). To provide empirical evidence to support the general trends and reinforce the techniques employed a series of Pearsons correlations and simple regressions were used. Pearsons correlations were conducted between the dependent variables and activation of each muscle at 0.01 seconds intervals from 0.25 seconds before to 0.1 seconds after peak velocity during the left and right stroke. The same procedure was then conducted between the independent variables and force data recorded at the left and right blade during the left and right paddle stroke. Significant Pearsons correlations identified between variables were followed up using simple regressions to identify predictive relationships.

4.7. Results

4.7.1 Technique Analysis

The technique outlined during the introduction (p.12 – 16) (Kemecsey, 1986), is the technique against which comparisons will be drawn, through the use of the joint angle, muscular activation, velocity and force production data. Furthermore for the purpose of analysis of the data the motions of the stroke will be divided into the four distinct phases identified by Kemecsey (1986) and Plagenhoef (1979), including the catch (green), power maintenance (red), recovery (blue) and air work (pink) phases. Each of the phases are presented on the charts of data traces by the diagrams above the dashed boxes.

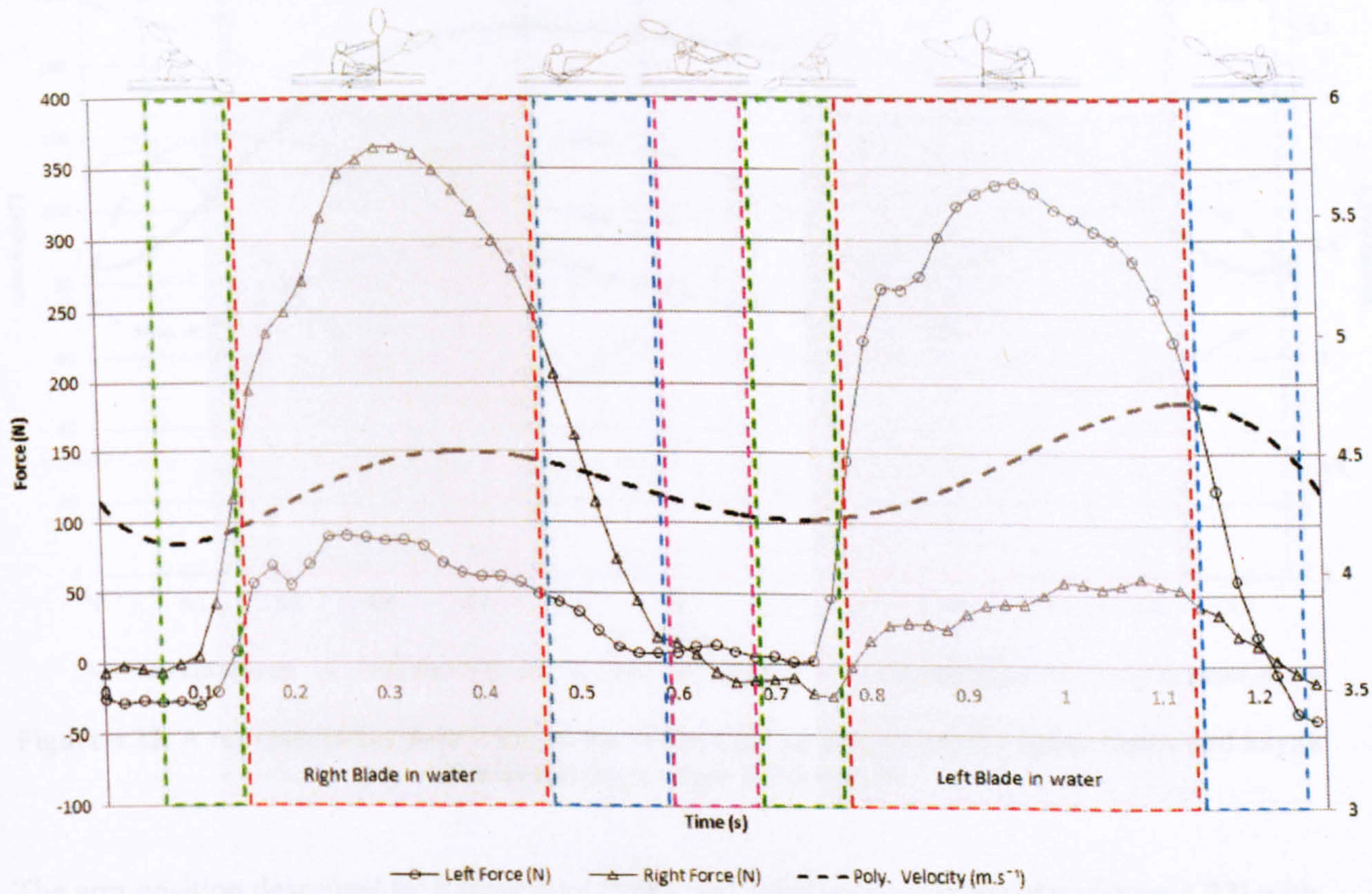


Figure 4.21. A representative data trace of the subject group displaying force production and kayak velocity during a single stroke cycle.

The relationships between force production and kayak velocity was clearly apparent form the visual inspection of the data (figure 4.21), characterised by the velocity increasing as force increased, with the force peaking at the mid-point of the stroke prior to peak velocity. Thus indicating that kayak velocity is dependent upon force production. However these factors are products and not constituents of technique, therefore it is important to establish the motions and muscular activation of the limbs and muscles that result in these findings. During analysis the terms ipsilateral and contralateral will be used to discuss the body limbs and joints with reference to the stroke of interest, for example during the right paddle stroke the right elbow will be term the ipsilateral elbow and the left elbow the contralateral elbow.

4.7.1.1. The Catch (green)

Kemecsey (1986) expressed the catch as a position in which the ipsilateral side of the body is set with the shoulder and hip are rotated forward, with the arm fully extended forward and the knee and hip flexed.

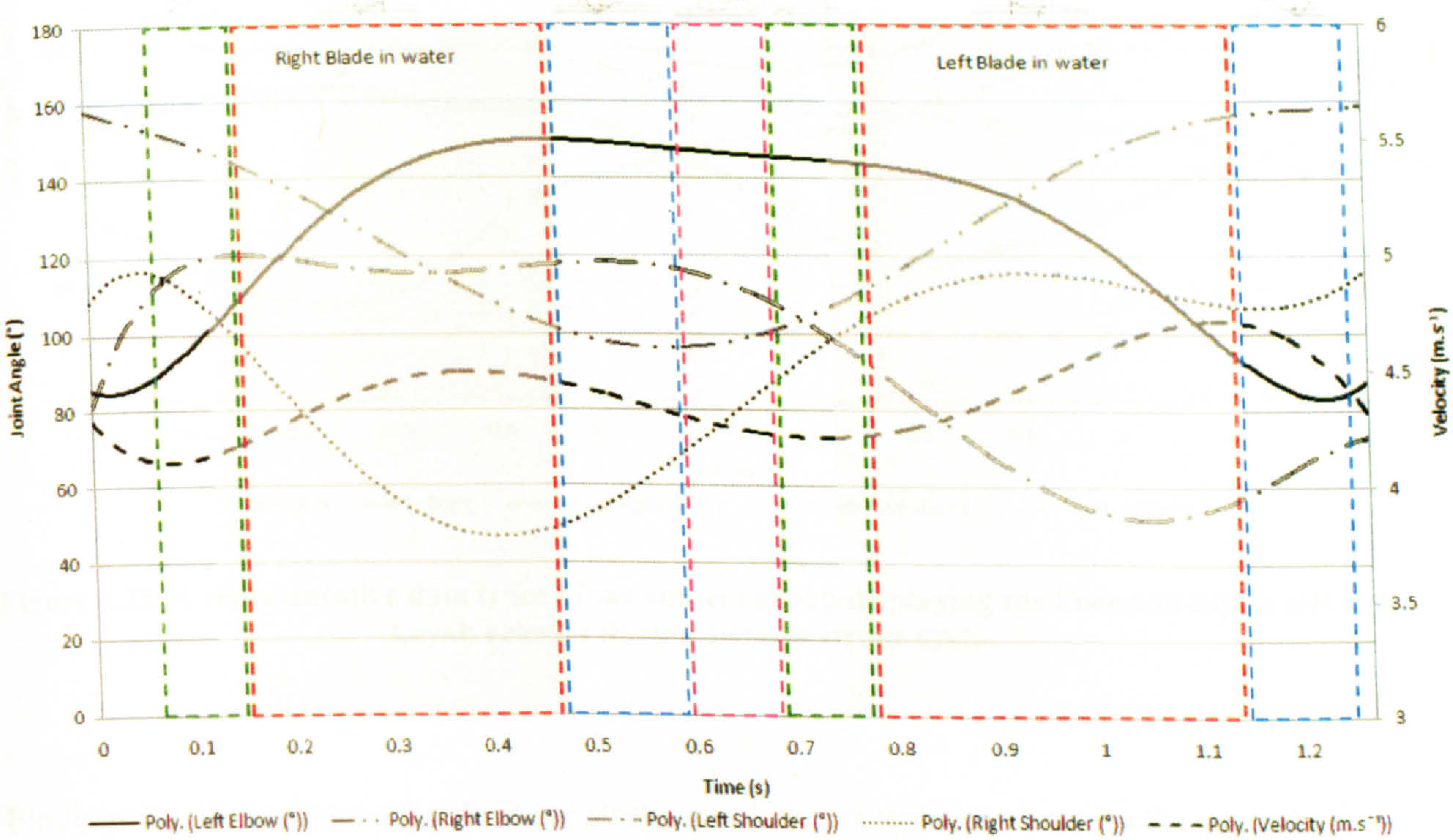


Figure 4.22. A representative data trace of the subject group displaying the upper limbs and kayak velocity during a single stroke cycle.

The arm position described by Kemecsey (1986) was supported in the results (figure 4.22) with the ipsilateral elbow displaying an angle of 145° or greater as the paddle was prepared to enter the water. Simultaneously the ipsilateral shoulder was identified to be in a flexed position of 115° to 120° as the subjects reached forward to paddle entry. Additionally the trunk position displayed a similar orientation to that outlined by Kemecsey (1986), rotated to a position in which the ipsilateral shoulder was ahead of the contralateral, allowing a greater forward reach (figure 4.25). The orientation of the ipsilateral hip provided further support to Kemecsey's (1986) technique with flexion clearly evident during the catch. However disparity was established between the position of the ipsilateral knee proposed by Kemecsey (1986), as the electrogoniometer traces identified that although the ipsilateral knee was flexed (figure 5.23), an extension movement was occurring throughout the catch phase, as the rectus femoris activation dissipated.

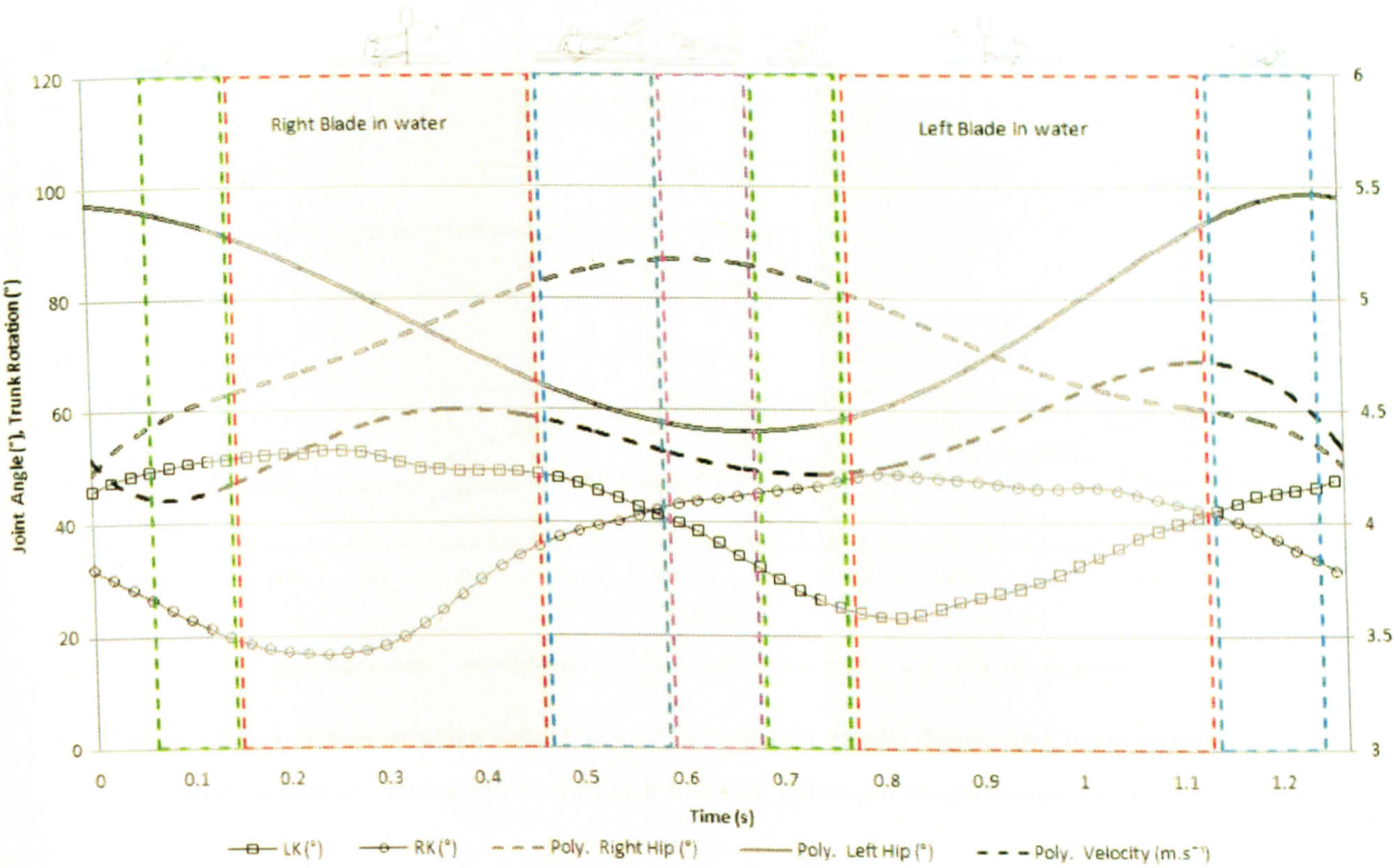


Figure 4.23. A representative data trace of the subject group displaying the knee and hip angles and kayak velocity during a single stroke cycle.

Findings for the contralateral side of the stroke similarly presented support for the upper limb and trunk positions outlined by Kemecsey (1986). Kemecsey (1986) proposed that the contralateral side of the body should be set with the arm flexed at the elbow and the shoulder abducted as the knee is in extension (Kemecsey, 1986). Findings identified corroborating evidence in the position of the elbow and shoulder for Kemecsey's (1986) technique, as the elbow was flexed and the shoulder was abducted (figure 4.22). The contralateral knee did not support Kemecsey's (1986) technique, with the knee flexing throughout the catch phase (figure 4.23). Simultaneously prominent activation of the contralateral gastrocnemius was presented indicating that the gastrocnemius could be the prime mover in knee flexion (figure 4.24). The musculature of the trunk also displayed the initiation of the major contractions in the catch phase of the stroke, with the rectus abdominus and ipsilateral latissimus dorsi activation beginning to climb. This could be a preparatory activation setting the muscles to allow an effective stroke.

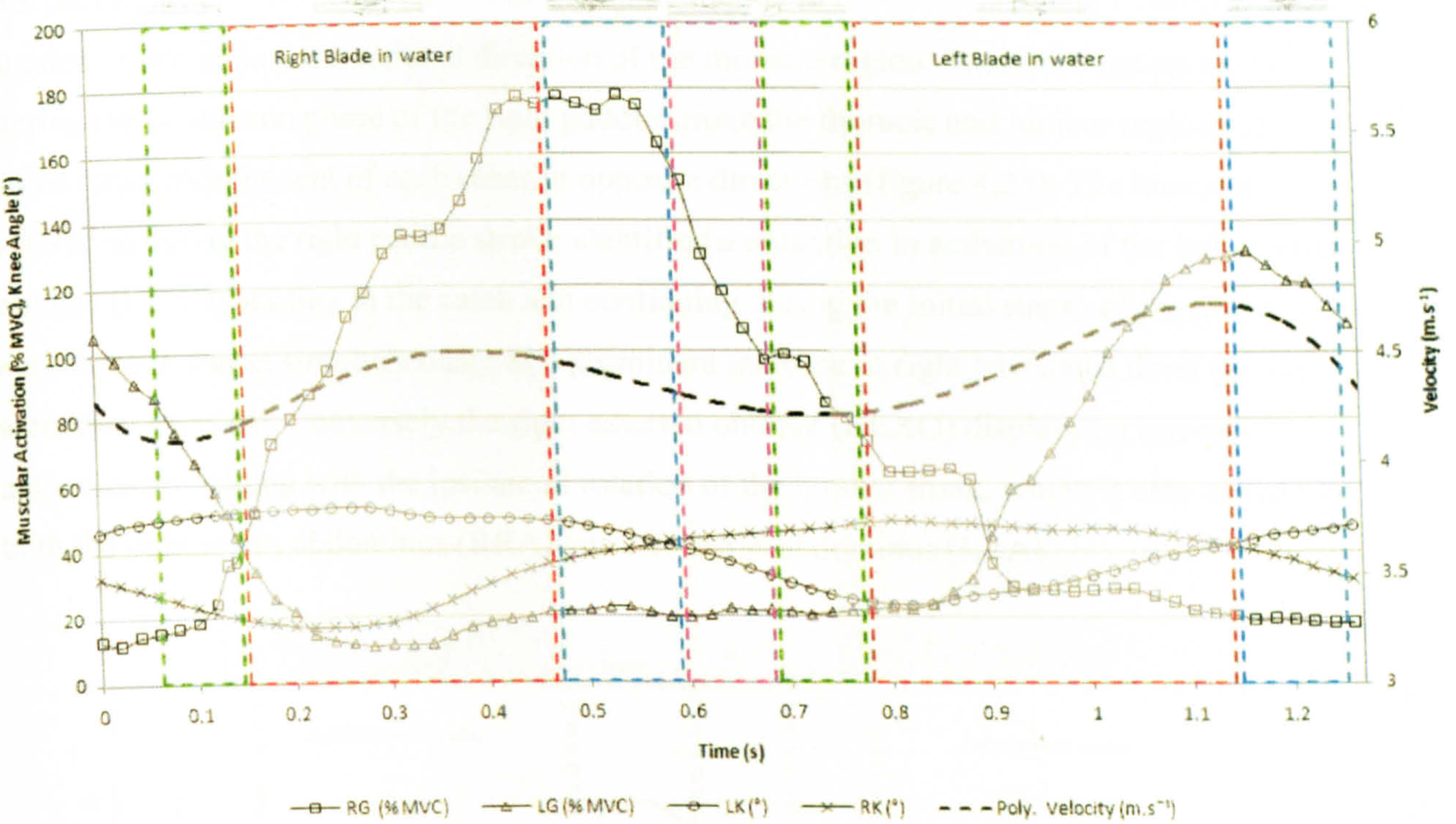


Figure 4.24. A representative data trace of the subject group displaying knee motion, gastrocnemius activation and kayak velocity during a single stroke cycle.

4.7.1.2. The Power Maintenance Phase (red)

Kemecsey (1986) indicates that the power maintenance phase should begin with the trunk, ipsilateral shoulder and hip rotating backwards, simultaneously the shoulder should flex and abduct, whilst the elbow stays extended and the hip and knee begin to extend. The contralateral side of the body is characterised by the shoulder holding a flexed abducted position before adducting through the stroke, with the elbow moving through extension and the hip and knee starting at the point of greatest extension before flexing throughout the stroke.

The torsiometer data traces both support and conflict with Kemecsey's (1986) proposed trunk motion. During the right paddle stroke the thoracic region displaying a peak rotation to the ipsilateral side early in the power/maintenance phase, followed by a rotation to the contralateral side supported Kemecsey's (1986) notion of trunk rotation. This coincided with the increase in latissimus dorsi activation on the ipsilateral side. However the thoracic region did not reach a neutral anatomical position during this initial rotation, which was followed by the initiation of an abrupt rotation back toward the ipsilateral side at the end of the power maintenance phase (figure 4.25). The analysis of the lumber region displayed contradictory evidence to Kemecsey's (1986) technique, exhibiting an increasing rotation to the ipsilateral side throughout the paddle stroke. The peak rotation of the lumbar spine to the ipsilateral side coincided with the sudden alteration in the rotational direction of the thoracic region. Therefore indicating that during the propulsion phase of the right paddle stroke the thoracic and lumbar regions of the spine rotate independent of each other in opposite directions (figure 4.25). The muscular activation during the right paddle stroke identified a reduction in activation of the left external oblique (LEXO) starting in the catch and continuing during the initial stages of the power maintenance phase, simultaneously as a prominent increase in right latissimus dorsi (RLD) activation occurred. Conversely the right external oblique (REXO) displays an increase in activation coinciding with the ipsilateral rotation of the lumbar trunk, which is also evident in both the right rectus abdominus (RRA) and left rectus abdominus (LRA).

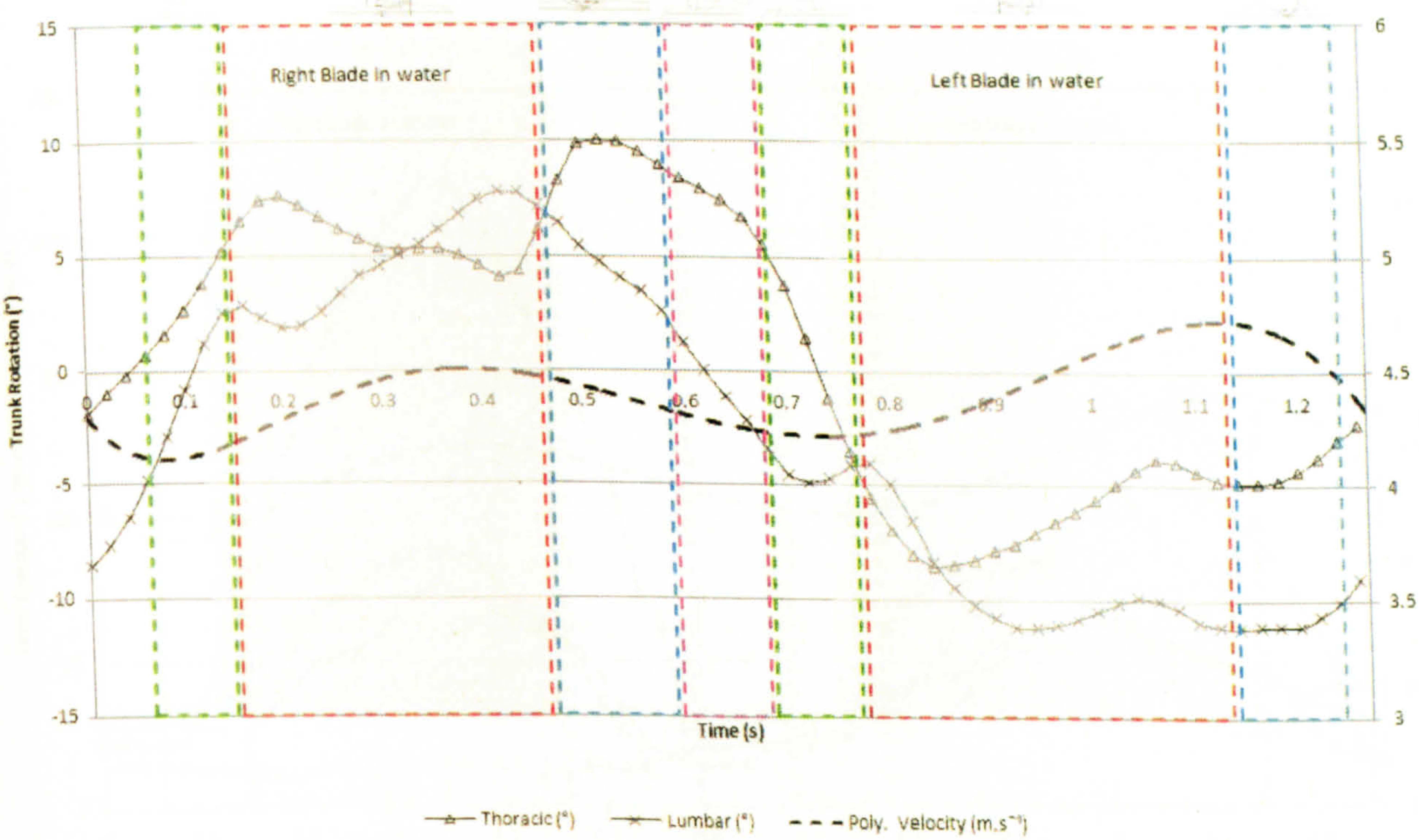


Figure 4.25. A representative data trace of the subject group displaying the rotation of the thoracic and lumbar spine and kayak velocity during a single stroke cycle.

The left paddle stroke displayed greater similarity between thoracic and lumbar spinal motion, both of which supported Kemecsey's (1986) technique, the ipsilateral rotation of the thoracic spine peaking early in the stroke before beginning to rotate contralaterally. The lumbar spine peaked in ipsilateral rotation midway through the stroke and generally holding this position until the recovery phase. Muscular activation displayed similar patterns to the right paddle stroke with the RRA and LRA exhibiting an onset of activation at the start of the power maintenance phase, with the left latissimus dorsi (LLD) data trace displaying an increase in activation from the beginning of the stroke.

The motion of the shoulders corroborated Kemecsey's (1986) technique, displaying a reduction in the ipsilateral shoulder angle continuing from its initiation during the catch and throughout the power maintenance phase as the paddle moves backward and away from the centre line of the kayak. However, the angle of the elbows during the power maintenance phase displayed clear disagreement with the motions outlined by Kemecsey (1986), who indicated that the elbow should stay extended. Conversely findings indicated that the ipsilateral elbow flexed in a parallel motion with the ipsilateral shoulder (figure 4.22), starting during the catch and continuing throughout the power maintenance phase. The contralateral shoulder and elbow followed the technique set out by Kemecsey (1986) with the shoulder adducting and the elbow extending throughout the stroke.

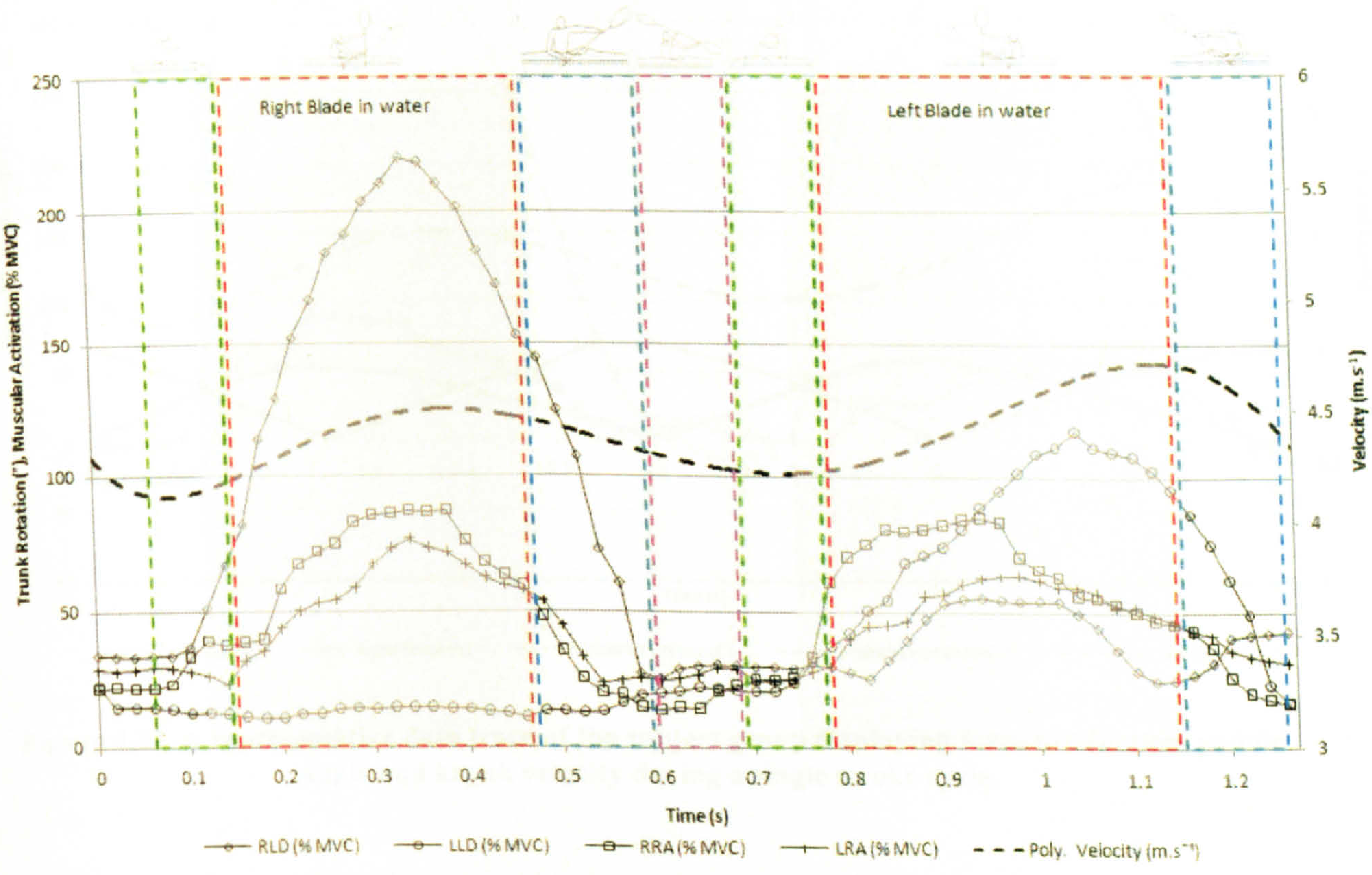


Figure 4.26. A representative data trace of the subject group displaying latissimus dorsi and rectus abdominus activation and kayak velocity during a single stroke cycle.

Further inconsistencies between Kemecsey's (1986) technique and the observed measures were apparent in the lower limbs. The ipsilateral knee continued extension at the beginning of the power maintenance phase; however the extension soon peaked around 20° of flexion holding this position before beginning to flex through the rest of the phase. Coinciding with this knee motion the highest levels of ipsilateral gastrocnemius activation are recorded, reinforcing the role of the gastrocnemius as the prime mover of knee flexion knee during paddling (figure 4.24). Further support is provided to this theory by the absence of activation within the biceps femoris. Conversely the ipsilateral hip depicted results supporting Kemecsey's (1986) technique with maximal flexion during the catch and extending throughout the power maintenance phase. Simultaneously the hip and knee on the contralateral stroke side displayed some similarities with Kemecsey's (1986) technique, the hip provided support as it was near full extension though flexion had already begun prior to the power maintenance phase. The contralateral knee provided no corroborative evidence starting in a flexed position which was held throughout the contralateral stroke.

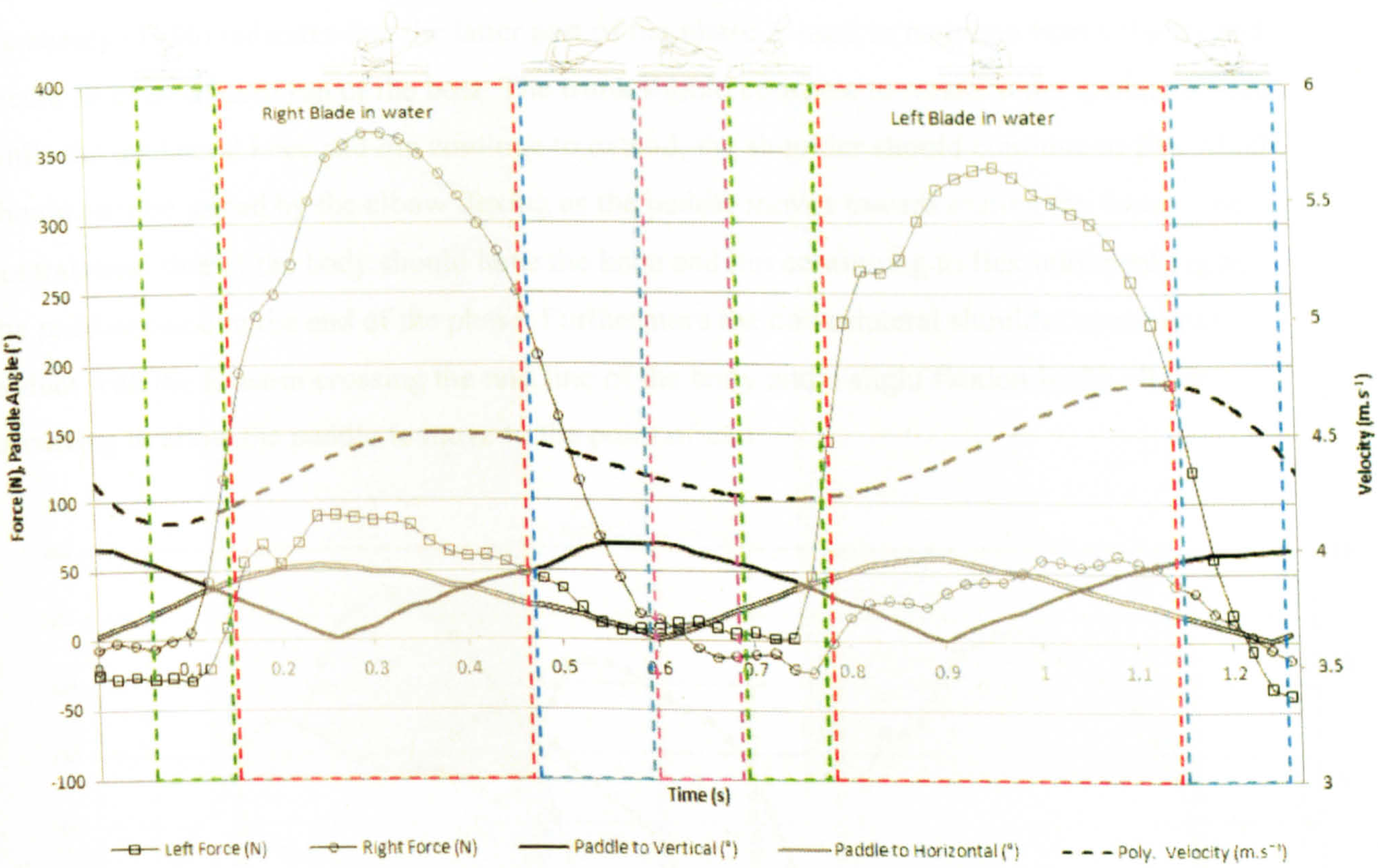


Figure 4.27. A representative data trace of the subject group displaying force production, paddle angle and kayak velocity during a single stroke cycle.

As the nomenclature of the phase would indicate the power maintenance phase is key in the development of force and ultimately the changes in boat velocity. Clear evidence to support this is presented in figure 4.27 with peak force occurring at the midpoint of the stroke, coinciding with an increase in boat velocity which peaks as the force begins to diminish in the latter stages of the stroke. Furthermore secondary minor peaks in force were apparent, coinciding with the maximal peak on the contralateral side. The minor force peak registered on the contralateral side of the stroke may be resultant of a bracing force applied by the top arm during the stroke, providing a resistance to aid force production during the paddle stroke. Moreover the main propulsive force peaks coincided with muscle activation peaks in the ipsilateral latissimus dorsi and the ipsilateral and contralateral rectus abdominus, indicating an important role in the production of peak force (figure 4.26).

Additionally the orientation of the paddle displayed an interaction with the muscle activation and peak force (figure 4.27) reaching a vertical position momentarily before the peaks occurred, providing support to the theory that a vertical paddle position is important in kayak propulsion (Plagenhoef, 1979; Mann and Kearney, 1980; Sanders and Kendal, 1992; Sanders and Baker, 1998).

Kemecsey (1986) indicates that the latter part of the phase is used to maintain boat velocity and secure an even smooth run of the boat. The trunk should continue to rotate to the ipsilateral side while the ipsilateral knee and hip continue to extend, the shoulder should continue to flex which should now be joined by the elbow flexing as the paddle moves toward exiting the water. The contralateral side of the body should have the knee and hip continuing to flex until peaking as the paddler come to the end of the phase. Furthermore the contralateral shoulder continues to adduct with the forearm crossing the mid line of the body and a slight flexion in the elbow occurring to allow the paddle to move to the point of exit.

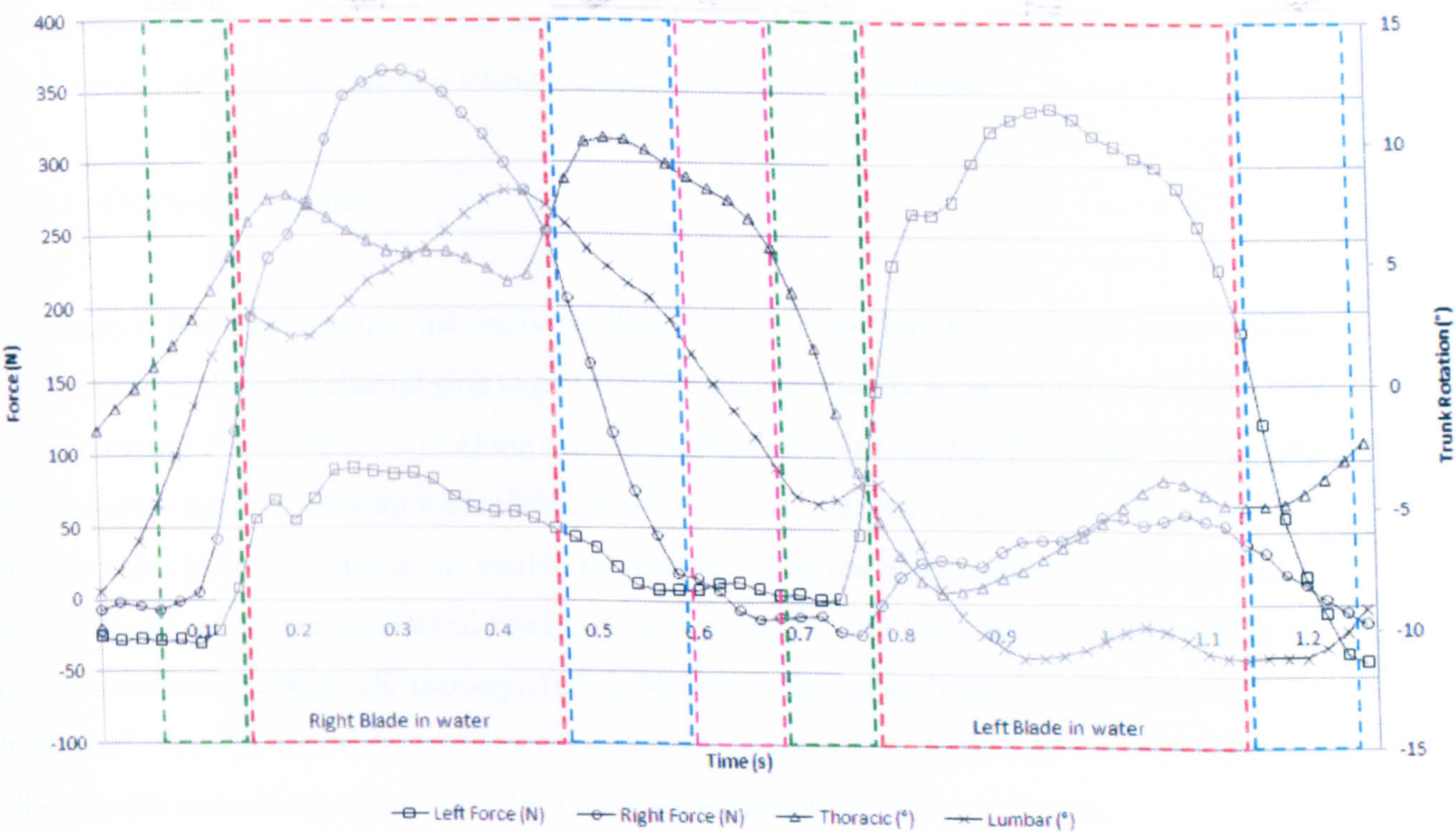


Figure 4.28. A representative data trace of the subject group displaying rotation in the thoracic and lumbar spinal regions and force production during a single stroke cycle.

The rotation in the thoracic region of the spine during the right paddle stroke continued to rotate toward the contralateral side until an abrupt rotation back to the ipsilateral side, as the lumbar spine starts to rotate to the contralateral side (figure 4.28). This could be a result of the need to maintain the smooth running of the kayak with the sudden change in thoracic rotation compensating for the change in lumbar direction to hold the kayak straight to limit lateral tilt of the kayak. Furthermore no muscular activity was identified that could explain the change in trunk rotation at the end of the right paddle stroke. The trunk rotation data for the left paddle stroke did not display the same rapid rotation back to the ipsilateral side therefore not supporting the theory of its importance of ensuring a smooth running of the kayak.

The shoulders continued to provide support to Kemecsey's (1986) technique displaying continual flexion in the ipsilateral side and the contralateral shoulder continues to hold its angle of flexion throughout the phase. The latter stage of the phase identified further support for Kemecsey's (1986) technique in the ipsilateral elbow as the data traces of the elbow angle displayed the flexion predicted. The contralateral elbow an extended position, therefore not supporting Kemecsey (1986) indication that there would be slight flexion preparing for blade exit from the water. Furthermore the ipsilateral hip continues to extend corroborating Kemecsey's (1986) technique, though the ipsilateral knee continues to oppose the proposed technique by increasing flexion throughout the latter stages of the stroke. The joint angles of the contralateral lower limb are characterised by the knee holding a flexed position and the hip continuing to flex, further substantiating Kemecsey's (1986) technique.

4.7.1.3. The Recovery (blue)

Kemecsey (1986) outlines that the recovery phase is very important as it is at this point that the torso rotates to the contralateral side to position the body correctly to make the next catch. This rotation causes the kayak to twist along the longitudinal axis increasing the wetted surface area and therefore the drag causing a deceleration of the kayak. Furthermore the recovery phase is characterised by an increase in the ipsilateral hip flexion as the ipsilateral knee maintains its level of extension and contralateral knee and hip hold their flexed positions from the end of the power maintenance phase (Kemecsey, 1986). Motion in the upper limbs is defined by the ipsilateral shoulder beginning to abduct and the elbow continuing to flex, as the contralateral elbow holds extension and the shoulder increases in flexion (Kemecsey, 1986).

The rotation of the trunk and reduction in kayak velocity is clearly supported in the data (figure 4.25) with a clear reduction in velocity by on average $1.49 m.s^{-1}$ during the recovery phase simultaneously as the greatest rate of rotation takes place in both the thoracic and lumbar spinal regions and as the contralateral external oblique displays prominent activation. Further support is identified for Kemecsey's (1986) technique in the contralateral hip and knee both holding their position during the recovery phase. To which both the contralateral gastrocnemius and rectus femoris display activation. This further supports the gastrocnemius flexing the knee and the rectus femoris as having an important role in flexing the hip. The ipsilateral hip did not reinforce Kemecsey's (1986) technique with the hip continuing to extend during the recovery phase and the knee continuing to flex due to activation of the gastrocnemius. The ipsilateral shoulder displayed an increase in angle caused by an abduction of the shoulder, therefore supporting Kemecsey's (1986) technique; however the contralateral shoulder displayed no increase in flexion prior during the recovery phase. The ipsilateral elbow supports Kemecsey's (1986) technique continuing to flex before platueaing at the end of the recovery phase while the contralateral shoulder displayed contradictory results with a slow flexion throughout the recovery.

4.7.1.4. The Air work (pink)

Kemecsey (1986) indicates that the air work allows for a presetting of the muscles and joints to allow a more proficient catch and maintenance phase. This was identified in the results as the trunk continued to rotate to the contralateral side, resulting in the contralateral shoulder moving forward to the position required for the catch of the contralateral stroke. Further support was provided as the extension of the contralateral elbow increases to maximal levels during the trials and the shoulder angle increases as the subjects prepared for paddle entry. While the muscles that displayed prominent activation in the prior stroke return to resting levels and the muscles required for the forthcoming stroke display signs of preparatory activation. Additionally Kemecsey (1986) indicates that the trunk should start to rotate slightly earlier than the shoulders for best technique to be achieved, although this was not evident in the results there was an earlier rotation in the lumbar region than the thoracic region, which may be the cause of Kemecsey's (1986) theory (figure 4.25).

Kemecsey (1986) indicates that an identical paddling technique should be employed during both left and right stroke; however this was not apparent in the recorded data traces. The rectus abdominus, latissimus dorsi, gastrocnemius, biceps femoris and rectus femoris displayed similar patterns of activation, while the shoulders, elbows, knees and hips also displayed similar patterns. However, the levels of activation and angles recorded at the joints displayed clear differences between left and right paddle strokes. These asymmetries were even more prevalent within the external obliques and trunk rotation (figure 4.25) clearly indicating that asymmetry exists within technique.

4.7.2. Statistical Analysis

Across all subjects mean velocity was identified at 4.78 ± 0.45 $m.s^{-1}$ (range: 4.34 $m.s^{-1}$ to 5.55 $m.s^{-1}$). Average intra stroke peak velocity was 5.25 ± 0.48 $m.s^{-1}$ (range: 4.79 $m.s^{-1}$ to 6.08 $m.s^{-1}$) during the left paddle stroke and 5.23 ± 0.53 $m.s^{-1}$ (range: 4.77 $m.s^{-1}$ to 6.28 $m.s^{-1}$) during the right paddle stroke. The average mean force generated at the left blade was 239.9 ± 13.5 N (range 216.5 N to 260.3 N), with right blade force exhibiting a significantly lower ($P < 0.05$) average mean force of 208.3 ± 17.4 N (range: 181.7 N and 227.2 N). The average peak force during the left paddle stroke was 365.2 ± 24.7 N (range: 327.0 N and 401.8 N) and 343.6 ± 43.1 N (range: 266.1 N to 393.7 N) during the right paddle stroke. Total impulse during the left paddle stroke was recorded at 19366.8 ± 2718.6 N.s (range: 16300.3 N.s to 24869.0 N.s), the total impulse during the right paddle stroke was 19198.3 ± 4100.6 N.s (range: 15950.1 N.s to 28506.8 N.s).

Table 4.1. Velocity, Force and Temporal variables for the left paddle stroke.

Subject	Mean Velocity ($m.s^{-1}$)	Peak Velocity ($m.s^{-1}$)	Mean Force (N)	Peak Force (N)	Total Impulse (N.s)	Time to peak force (s)	Time to paddle exit (s)
1	5.55	6.08	248.5	379.9	32600.3	0.164	0.201
2	5.25	5.85	240.3	377.2	37497.4	0.175	0.217
3	4.63	5.09	230.0	369.3	34307.4	0.157	0.226
4	4.4	4.89	239.5	347.5	49738.0	0.179	0.269
5	4.36	4.79	216.5	327.0	41591.6	0.221	0.231
6	4.73	5.04	250.7	378.3	34641.5	0.204	0.187
7	4.96	5.40	260.3	401.8	40018.0	0.153	0.238
8	4.34	4.88	233.6	340.3	39474.5	0.192	0.218
Mean	4.78	5.25	239.9*	365.2	38733.6	0.181	0.223
St. Dev	0.45	0.48	13.5	24.7	5437.2	0.024	0.025
St. Error	0.16	0.17	4.8	8.8	2899.6	0.008	0.009

*** denotes significant difference between left and right paddle strokes *P<0.05***

The average time to peak force was 0.181 ± 0.024 s after the paddle entered the water (range: 0.153 s to 0.221 s) during the left paddle stroke. The right paddle stroke average time to peak force was 0.185 ± 0.022s (range: 0.154 s to 0.222 s). The time taken from the point of peak force to exit of the paddle was longer than the time taken to reach peak force averaging 0.223 ± 0.025 s (range: 0.187 s to 0.269 s) and 0.244 ± 0.036 s (range: 0.200 s to 0.323 s) during the left and right paddle strokes, respectively.

Table 4.2. Velocity, Force and Temporal variables for the right paddle stroke.

Subject	Mean Velocity ($m.s^{-1}$)	Peak Velocity ($m.s^{-1}$)	Mean Force (N)	Peak Force (N)	Total Impulse (N.s)	Time to peak force (s)	Time to paddle exit (s)
1	5.55	6.28	227.2	393.7	33007.0	0.160	0.219
2	5.25	5.64	215.6	369.0	38838.8	0.222	0.200
3	4.63	4.93	196.9	310.8	33409.4	0.154	0.255
4	4.4	4.78	220.9	378.2	57013.6	0.191	0.323
5	4.36	4.77	188.0	313.7	33481.0	0.194	0.238
6	4.73	5.24	225.7	369.6	39883.1	0.174	0.248
7	4.96	5.37	210.2	347.8	39638.9	0.188	0.244
8	4.34	4.81	181.7	266.1	31900.1	0.200	0.228
Mean	4.78	5.23	208.3*	343.6	38396.5	0.185	0.244
St. Dev	0.45	0.53	17.4	43.1	8201.2	0.022	0.036
St. Error	0.16	0.19	6.2	15.3	1922.3	0.008	0.013

*** denotes significant difference between left and right paddle strokes *P<0.05***

The range of joint motion, presented in table 5.3, identified that the right hip presented an average range of 99.2 ± 6.9° and the left an average of 96.7 ± 5.0°. The maximum angle produced at the hip was identical with both sides exhibiting a joint angle of 150.2°, therefore indicating that the minimum angle (point of greatest flexion) was the source of the difference between the sides. Furthermore the minimum left hip angle was significantly correlated with peak velocity, from which regression analysis identified a significant positive predictive relationship between minimal left hip angle and peak velocity during the left paddle stroke (R^2 = 0.507, $P < 0.05$). However, no other significant correlations or relationships were exhibited between the maximal and minimal joint angles of the hips and the independent variables.

No significant differences were evident in the maximum and minimum knee angle and the range of knee motion between the left and right sides, the left knee moving through a range of motion of 34.4 ± 9.0° on average and the right through 30.6 ± 9.7°. The rotation of the trunk also displayed no significant differences in the range of motion of the thoracic spinal region (mean 23.4 ± 5.6°) and lumbar spinal region (mean 24.1 ± 10.4°). Deconstructing the trunk rotations into left and right sides identified interesting findings with the subjects appearing to rotate to the right more at the lumbar spine and to the left more at the thoracic region. The trend in the lumbar spine was supported during inspection of the data traces during the technique analysis, clearly evident in figures 4.17 and 4.25. However, statistical analysis did not support this trend, identifying that there were no significant differences between the rotation of the thoracic and lumbar to either the left or right side. Further statistical analysis identified significant negative correlations between the range of lumbar rotation and the peak velocity during the left and right strokes. In addition significant negative correlations were established between the range of lumbar rotation and mean velocity during both left and right strokes. Application of linear regression analysis identified that these significant correlation displayed further significant predictive strength, characterised by an inverse relationship between lumbar region rotation and boat velocity, and therefore as lumbar spine range of motion decreased boat velocity increased. This relationship is reinforced within the technique analysis, with the greatest change in lumbar rotation, occurring between paddle strokes, coinciding with a clear reduction in boat velocity (figure 4.25). These findings indicate that the lower trunk is required to be held in a stable position throughout the stroke possibly allowing the efficient transfer of force to the kayak. The thoracic spinal region displayed no significant relationships with either boat velocity or force production.

Table 4.3. Maximum, Minimum and range of motion of the lower limb joint and trunk rotation angles.

Subject Number	Right Knee (°)		Left Knee (°)		Thoracic (°)		Lumbar (°)		Right Hip (°)		Left Hip (°)	
	Max	Min	Max	Min	Left	Right	Left	Right	Max	Min	Max	Min
1	38.2	7.7	62.4	38.6	9.4	11.4	4.9	7.1	146.3	56.7	166.5	69.3
(range)	*(30.5)*		*(23.8)*		*(20.8)*		*(12)*		*(89.6)*		*(97.2)*	
2	28.0	14.3	34.8	-1.3	13.8	18.3	-	-	159.7	61.0	151.3	58.5
(range)	*(13.7)*		*(36.1)*		*(32.1)*		*(-)*		*(98.7)*		*(92.8)*	
3	50.4	10.8	49.7	10.4	11.6	11.4	18.4	19.9	156.0	66.2	156.0	65.1
(range)	*(39.6)*		*(39.3)*		*(23.0)*		*(38.3)*		*(89.8)*		*(90.9)*	
4	48.5	15.4	54.1	19.6	23.4	0.5	3.5	21.7	144.2	39.6	153.9	46.4
(range)	*(33.1)*		*(34.5)*		*(23.9)*		*(25.2)*		*(104.6)*		*(107.5)*	
5	41.0	12.7	41.0	31.8	11.3	12.1	20.8	16.8	151.1	43.2	141.0	44.2
(range)	*(28.3)*		*(26.0)*		*(23.4)*		*(37.6)*		*(107.9)*		*(96.8)*	
6	53.6	10.0	46.8	4.1	5.5	6.9	9.2	7.6	152.1	55.3	145.7	49.4
(range)	*(43.6)*		*(42.8)*		*(12.4)*		*(16.8)*		*(96.8)*		*(96.3)*	
7	56.5	21.1	47.2	-0.9	15.7	11.5	8.0	8.5	150.5	45.2	144.5	46.7
(range)	*(35.4)*		*(48.1)*		*(27.2)*		*(16.5)*		*(105.3)*		*(97.8)*	
8	45.7	24.8	44.6	20.3	12.1	12.6	10.3	12.3	141.3	40.8	142.6	48.3
(range)	*(20.9)*		*(24.2)*		*(24.7)*		*(22.6)*		*(100.5)*		*(94.3)*	
Mean	45.2	14.6	49.7	15.3	13.0	10.4	10.7	13.4	150.2	51.0	150.2	$53.5^{\$}$
	(30.6)		*(34.4)*		*(23.4)*		*($24.1^{\wedge*\$\#}$)*		*(99.2)*		*(96.7)*	
St. Dev	9.2	5.8	8.5	14.9	5.0	5.3	6.5	6.1	6.1	10.1	8.5	9.5
	(9.7)		*(9.0)*		*(5.6)*		*(10.4)*		*(6.9)*		*(5.0)*	
St. Error	3.3	4.2	3.0	5.3	1.8	1.9	2.5	2.3	2.2	3.6	3.0	3.4
	(3.4)		*(3.2)*		*(2.0)*		*(3.9)*		*(2.4)*		*(1.8)*	

Significant relationship ($P<0.05$) with mean velocity during the left stroke is signified by ^, Significant relationship ($P<0.05$) with mean velocity during the right stroke is signified by *, Significant relationship ($P<0.05$) with peak velocity during the left stroke is signified by $, Significant relationship ($P<0.05$) with peak velocity during the right stroke is signified by #.

The position of the upper body joints displayed similarities between sides, with the left and right shoulder range of motion separated by only 0.2° (left 131.4 ± 6.0°; right 131.6 ± 5.8°). The elbows displayed similarities with the right elbow displaying a range of motion of 151.1 ± 11.6° and the left a range of motion of 147.1 ± 4.2°. The joint angles and range of motion of the shoulders and the right elbow displayed no significant correlation with either velocity of force production on either side, however the left elbow range of motion did. The range of motion of the left elbow displayed a significant correlation with peak force during the right paddle stroke. Further statistical analysis identified that the relationship was stronger than a simple correlation and a significant predictive relationship was established between the left elbow range of motion and peak force during the right stroke from the linear regression analysis. This finding indicated that the contralateral arm plays an important role in the production of peak force.

Table 4.4. Maximum, minimum and range of motion for the joints of the upper limbs.

Subject Number	Left Elbow (°)		Right Elbow (°)		Left Shoulder (°)		Right Shoulder (°)	
	Max	Min	Max	Min	Max	Min	Max	Min
1	171.0	21.1	169.8	14.2	151.0	25.5	148.7	12.7
(range)	*(149.9)*		*(155.5)*		*(125.5)*		(136.0)	
2	165.3	16.1	172.8	34.5	149.8	9.6	152.5	19.1
(range)	*(149.2)*		*(138.3)*		*(140.2)*		(133.4)	
3	161.7	14.0	168.7	12.4	135.6	12.3	149.6	15.0
(range)	*(147.7)*		*(156.4)*		*(123.3)*		(134.7)	
4	161.0	8.3	164.6	23.9	142.1	15.6	138.0	9.4
(range)	*(152.7)*		*(140.7)*		*(126.5)*		(128.6)	
5	165.3	17.6	165.4	31.5	149.3	15.6	156.5	24.9
(range)	*(147.6)*		*(133.9)*		*(133.7)*		(131.6)	
6	166.5	21.8	174.2	10.1	153.4	19.9	152.1	32.4
(range)	*(144.7)*		*(164.1)*		*(133.5)*		(119.7)	
7	166.8	20.3	166.7	4.6	147.1	16.4	146.5	16.9
(range)	*(146.5)*		*(162.2)*		*(130.8)*		(129.6)	
8	166.9	28.2	169.9	12.4	154.2	16.8	147.6	8.8
(range)	*(138.6)*		*(157.5)*		*(137.4)*		(138.8)	
Mean	165.6	18.4	169.0	18.0	147.8	16.5	148.9	17.4
	(147.1$^{\phi}$)		*(151.1)*		*(131.4)*		*(131.6)*	
St. Dev	3.2	5.9	3.4	10.7	6.2	4.8	5.4	8.0
	(4.2)		*(11.6)*		*(6.0)*		*(5.8)*	
St. Error	1.1	2.1	1.2	3.8	2.2	1.7	1.9	2.8
	(1.5)		*(4.1)*		*(2.1)*		*(2.1)*	

Significant correlations (*P<0.05*) with peak force during the right paddle stroke is signified by $^{\phi}$

Table 4.5 shows the range of paddle to vertical and paddle to horizontal, which unsurprisingly displayed an inverse relationship. This relationship is characterised as an increase in the angle between the paddle and the vertical plane resulted in a decrease in the angle between the paddle and the transverse plane (see figure 4.27). In relation to the independent variable of force and velocity the paddle to horizontal angle displayed no relationship; however the paddle to vertical angle displayed a significant correlation and predictive relationship. The relationship was characterised by the greater the range of motion in the paddle to vertical angle the higher the mean velocity during the stroke. This does not support the apparent interaction between a vertical paddle angle and peak force identified during visual inspection used in the technique analysis in comparison with Kemecsey's (1986) technique. The average range of shoulder tilt in relation to the transverse plane was identified as 46.7 ± 5.4°; however no significant correlations with velocity or force production were exhibited.

Table 4.5. Ranges paddle angles and shoulder tilt.

Subject Number	Paddle to Vertical (°)	Shoulder Tilt to Horizontal (°)	Paddle to Horizontal (°)
1	70.3	40.7	76.2
2	70.7	40.9	64.7
3	64.9	53.9	72.3
4	73.0	48.7	72.0
5	69.2	54.3	64.7
6	76.3	45.2	71.2
7	75.1	47.5	67.0
8	70.8	42.5	66.0
Mean	71.3[£]	46.7	69.3
St. Dev	3.6	5.4	4.2
St. Error	1.3	1.9	1.5

Significant relationship ($P < 0.05$) with mean force velocity during the left stroke is signified by [£].

4.7.2.1. *Velocity and Force*

Initial analysis of force and velocity variables during the left paddle stroke exhibited significant left paddle correlations (table 4.6) between mean velocity and peak velocity ($r = 0.985$ $P < 0.001$), mean velocity and peak force ($r = 0.727$, $P = 0.02$), peak velocity and peak force ($r = 0.657$, $P = 0.04$), mean force and peak force ($r = 0.866$, $P < 0.01$) and peak force and the time to peak force ($r = -0.709$, $P = 0.02$).

Table 4.6. Correlation and Regression values for Peak and Mean Velocity and Force from Left Paddle Stroke.

	Mean Velocity		Peak Velocity		Mean Force		Peak Force	
	Corr.	R^2	Corr.	R^2	Corr.	R^2	Corr.	R^2
Mean Velocity								
Peak Velocity	0.985*	0.971*						
Mean Force	0.571		0.503					
Peak Force	0.727*	0.529*	0.657*	0.432	0.866*	0.750*		
Total stroke impulse	-0.585		-0.202		0.248		-0.202	
Time to Peak Force	-0.533		-0.179		-0.549		-0.709*	0.503*
Time from Peak Force to Paddle Exit	-0.442		-0.362		-0.227		-0.308	

* denotes significant to $p < 0.05$

Regression analysis explored these data further, identifying significant relationships between mean velocity and peak velocity ($R^2 = 0.971$, $P < 0.01$) and peak force and mean force ($R^2 = 0.750$, $P = 0.01$). Mean velocity displayed further significant predictive power with Peak force ($R^2 = 0.529$, $P < 0.01$), with peak force displaying a further significant predictive relationship with time to peak force ($R^2 = 0.503$, $P < 0.01$).

Table 4.7. Correlation and Regression values for Peak and Mean Velocity and Force from Right Paddle Stroke.

	Mean Velocity		Peak Velocity		Mean Force		Peak Force	
	Corr.	R^2	Corr.	R^2	Corr.	R^2	Corr.	R^2
Mean Velocity								
Peak Velocity	0.980*	0.961*						
Mean Force	0.638*	0.407	0.645*	0.416				
Peak Force	0.658*	0.433	0.656*	0.430	0.964*	0.929*		
Total stroke impulse	-0.203		-0.597		-0.124		-0.034	
Time to Peak Force	-0.127		-0.559		-0.200		-0.119	
Time from Peak Force to Paddle Exit	-0.575		-0.564		0.384		0.100	

* denotes significant to $p < 0.05$

The right paddle stroke correlation analysis highlighted significant correlations (table 4.7) between mean velocity and peak velocity ($r = 0.980$, $P < 0.01$), mean velocity and mean force ($r = 0.638$, $P = 0.04$), mean velocity and peak force ($r = 0.658$, $P = 0.04$), peak velocity and mean force ($r = 0.645$, $P = 0.04$), peak velocity and peak force ($r = 0.656$, $P = 0.04$), and mean force and peak force ($r = 0.964$, $P < 0.001$). Similar to the left paddle analysis the regression analysis of the right paddle stroke showed strong significant regression relationships between mean velocity and peak velocity ($R^2 = 0.961$, $P < 0.001$) and mean force and peak force ($R^2 = 0.929$, $P < 0.001$). These findings reinforced the apparent interaction between force and velocity identified during the technique analysis. All other significant correlations did not show any further significance at regression analysis (table 4.7).

4.7.2.2. Electromyography

Analysis of peak muscle activation identified significant correlations (table 4.8) between the left rectus femoris and mean velocity ($r = 0.67$, $P = 0.04$) and peak velocity ($r = 0.689$, $P = 0.03$) during the left paddle stroke. These correlations when tested through a linear regression displayed no significant predictive relationships. All other muscles demonstrated no significant correlation with mean or peak velocity.

Analysis of peak EMG activation and force production identified significant correlations between mean force and peak right gastrocnemius ($r = 0.698$, $P = 0.03$), peak left external oblique ($r = 0.801$, $P = 0.01$) and peak right ($r = 0.855$, $P < 0.01$) and left ($r = 0.680$, $P = 0.03$) rectus abdominus activation. Further investigation of the significant correlations demonstrated that the peak activation of the right gastrocnemius and left rectus abdominus displayed no significant predictive relationship with mean force. The linear regression analysis did identify significant predictive relationships between mean force and the right rectus abdominus ($R^2 = 0.731$, $P = 0.01$) and left external oblique ($R^2 = 0.642$, $P = 0.02$) peak activation (table 5.8).

Table 4.8. Correlation and regression findings for peak EMG activity during the left paddle stroke for peak and mean velocity and force.

	Mean Velocity		Peak Velocity		Mean Force		Peak Force	
	Corr.	R^2	Corr.	R^2	Corr.	R^2	Corr.	R^2
Right Rectus Femoris	0.404		0.349		0.570		0.516	
Left Rectus Femoris	0.670*	0.488	0.689*	0.475	0.323		0.431	
Right Biceps Femoris	-0.331		-0.246		-.0397		-0.489	
Left Biceps Femoris	0.266		0.331		0.042		0.390	
Right Gastrocnemius	0.436		-0.039		0.698*	0.487	0.477	
Left Gastrocnemius	-0.607		-0.484		-0.580		-0.812*	0.659*
Right Latissimus Dorsi ▲	-0.034		-0.113		0.396		0.564	
Left Latissimus Dorsi ▲	0.092		0.077		0.429		0.408	
Right External Oblique	0.311		0.195		0.249		0.143	
Left External Oblique	0.470		0.375		0.801*	0.642*	0.798*	0.637*
Right Rectus Abdominus	0.620		0.550		0.855*	0.731*	0.651*	0.424
Left Rectus Abdominus	0.415		0.291		0.680*	0.463	0.471	

* denotes significant relationships to $p < 0.05$, ▲ denotes significant difference in activation level between left and right stroke to $p < 0.05$

Similarly the peak force exhibited significant correlations with peak activation of the right rectus abdominus ($r = 0.651$, $P = 0.04$) and left external oblique ($r = 0.798$, $P = 0.01$), with the left external oblique demonstrating a significant predictive relationship ($R^2 = 0.637$, $P = 0.02$) from the regression analysis. The significant relationships between the peak rectus abdominus activation and force confirmed the simultaneous peaks at the mid-point of the stroke identified during the technique analysis. Additionally the left gastrocnemius had a significantly predictive relationship with peak force ($R^2 = 0.659$, $P = 0.01$) following a significant correlation ($r = -0.812$, $P = 0.01$).

Table 4.9. Correlation and regression findings for peak EMG activity during the right paddle stroke for peak and mean velocity and force.

	Mean Velocity		Peak Velocity		Mean Force		Peak Force	
	Corr.	R^2	Corr.	R^2	Corr.	R^2	Corr.	R^2
Right Rectus Femoris	0.430		0.413		0.228		0.352	
Left Rectus Femoris	0.778*	0.605*	0.751*	0.565*	0.719*	0.517*	0.806*	0.650*
Right Biceps Femoris	-0.339		-0.316		-0.384		-0.178	
Left Biceps Femoris	0.374		-0.234		-0.376		-0.394	
Right Gastrocnemius	0.353		-0.171		0.196		0.289	
Left Gastrocnemius	-0.308		-0.227		0.270		0.197	
Right Latissimus Dorsi	-0.098		-0.137		0.589		0.576	
Left Latissimus Dorsi	0.102		0.079		-0.452		-0.346	
Right External Oblique	0.690*	0.476	0.737*	0.543*	0.439		0.442	
Left External Oblique	0.776*	0.602*	0.703*	0.494	0.663*	0.440	0.643*	0.413
Right Rectus Abdominus	0.647*	0.418	0.659*	0.434	0.242		0.214	
Left Rectus Abdominus	0.498		0.478		0.944*	0.891*	0.955*	0.912*

* denotes significant relationships to $p < 0.05$, ▲ denotes significant difference in activation level between left and right stroke to $p < 0.05$

The analysis of the peak muscle activity during the right paddle stroke (table 4.9) identified significant correlations between mean and peak velocity and the left rectus femoris (MV: r = 0.778, P = 0.01; PV: r = 0.751, P = 0.02), right external oblique (MV: r = 0.690, P = 0.03; PV: r = 0.737, P = 0.02), left external oblique (MV: r = 0.776, P = 0.01; PV: r = 0.703, P = 0.03) and right rectus abdominus (MV: r = 0.647, P = 0.04; PV: r = 0.659, P = 0.04). Linear regression analysis highlighted significant relationships between mean velocity and left rectus femoris (R^2 = 0.605, P = 0.02) and left external oblique (R^2 = 0.602, P = 0.02). The left rectus femoris demonstrated another significant relationship with peak velocity (R^2 = 0.565, P = 0.03), as did the right external oblique (R^2 = 0.543, P = 0.04).

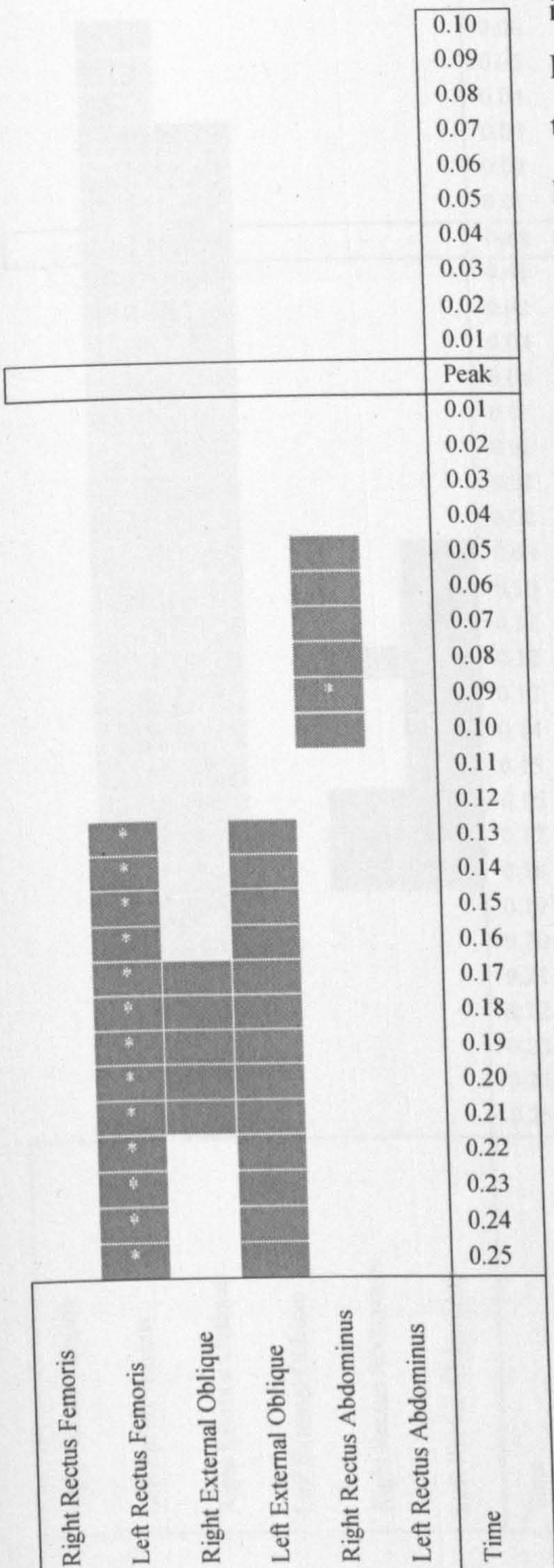
Analysis of mean and peak force exhibited significant correlations with peak activation of the left rectus femoris (MF: r = 0.719, P = 0.02; PF: r = 0.806, P = 0.01), left external oblique (MF: r = 0.663, P = 0.04; PF: r = 0.643, P = 0.04) and left rectus abdominus (MF: r = 0.944, P < 0.01; PF: r = 0.955, P < 0.01). The left rectus femoris (LRF) and left rectus abdominus (LRA) both presented further significant relationships with mean (LRF: R^2 = 0.517, P = 0.05; LRA: R^2 = 0.650, P < 0.01) and peak (LRF: R^2 = 0.891, P = 0.02; LRA: R^2 = 0.912, P < 0.01) velocity from the regression analysis.

From the regression analysis clear asymmetry between left and right paddle strokes appears to exist, with a greater number of significant relationships being identified between muscle activity during the right stroke (table 4.8). However comparison between the peak muscular activation during the left and right paddle strokes using independent t-tests identified that only the levels of activation in the latissimus dorsi could determine between left and right paddle strokes (table 5.9 and 5.9). The left latissimus dorsi displaying a significantly higher level of activation during the left paddle stroke (P = 0.01) and the right latissimus dorsi displayed a significantly (P = 0.05) higher level of activation during the right paddle stroke. This reinforces the asymmetry exposed during the technique analysis, most clearly exhibited within the rotation of the trunk.

4.7.3. Time Line Analysis

4.7.3.1. Muscular Activation

Table 4.10. Time line analysis of EMG activity with peak velocity during the left paddle stroke.



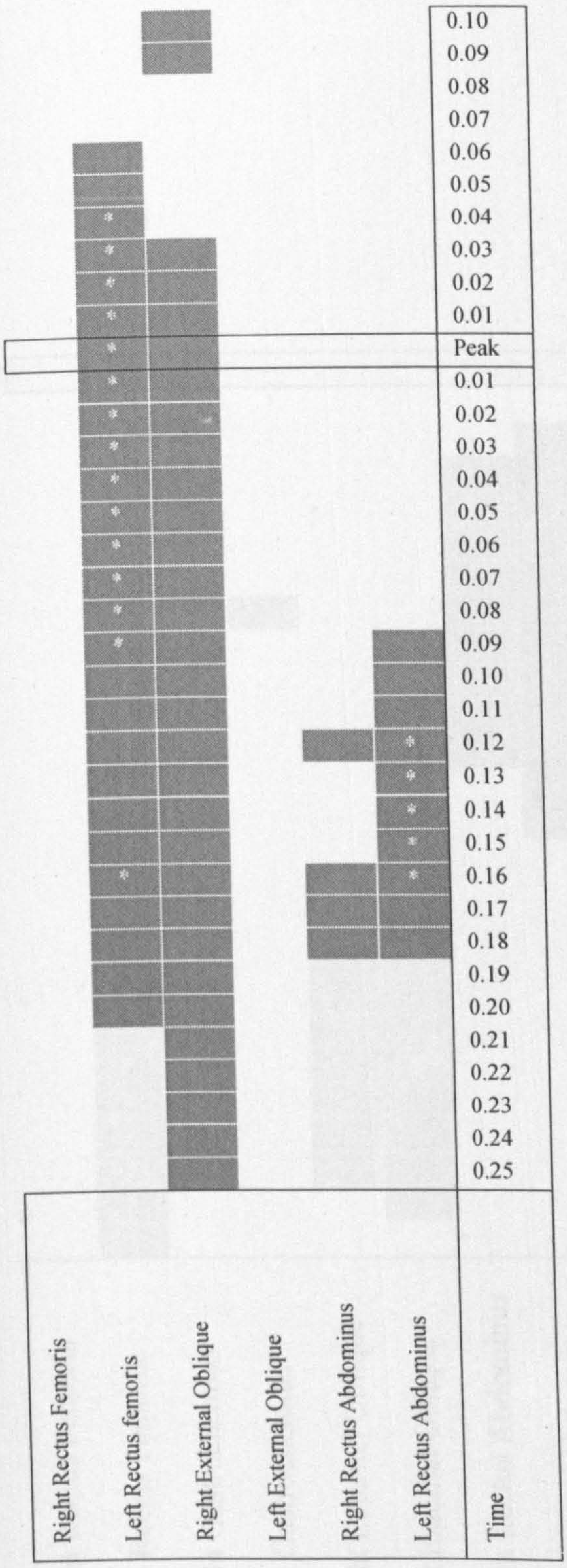
Denotes significant correlation

*** Denotes significant predictive relationship**

The time line analysis was conducted by normalising all subjects to peak velocity or peak force, dependent on the dependent variable under investigation (force or velocity). Using a series of Pearson's correlations and simple regressions at time points separated by 0.01 seconds pre and post peak intra stroke velocity and force, relationships between muscular activation or force measured with the dependent variables were derived. These were conducted in an attempt to establish the importance of timings of muscular contractions and force development during the stroke. Table 4.10 presents the significant correlations (signified by filled blue boxes) and regressions (signified by blue boxes with white asterisks) identified along the 0.25 seconds before to 0.1 seconds after peak velocity/force time line.

During the left paddle stroke the left rectus femoris exhibited a series of significant predictive relationships with peak velocity from 0.25 seconds to 0.13 seconds before peak velocity. This cluster of significances occurred simultaneously with the extension of the left knee during the catch and beginning of the power maintenance phase. Therefore the identification of the interaction of a cluster of significant relationships with knee extension and that a significant predictive relationship exists between peak velocity and peak left rectus femoris activation would indicate that the contraction of the left rectus femoris plays an important role in the production of peak boat velocity during the left paddle stroke. Coinciding with the cluster of significant relationships

Table 4.11. Time line analysis of EMG activity with peak velocity during the right paddle stroke.



Denotes significant correlation

*** Denotes significant predictive relationship**

identified between peak velocity and LRF activation a cluster of significant correlations were identified between peak velocity and the left external oblique (0.25 seconds to 0.13 seconds before peak). Additionally the right external oblique displayed a series of significant correlations from 0.21 seconds to 0.17seconds before peak velocity and the right rectus abdominus displayed a cluster of significant correlations with peak velocity from 0.1s to 0.05s before peak velocity, with a significant predictive relationship ($R^2 = 0.84$, $P = 0.03$) at 0.09 seconds before peak velocity.

During the right paddle stroke (table 4.11) the right external oblique (REXO) displayed significant correlation with peak velocity, supporting the clear interaction between REXO activation and the right paddle stroke identified during the technique analysis and the significant predictive relationship between peak activation and peak velocity. Similarly the left rectus femoris displayed an extended cluster of significant correlations (0.2 seconds before peak intra stroke velocity to 0.06 seconds after peak velocity) with peak velocity, supporting the significant predictive relationship exhibited between peak activation and velocity. Furthermore regression analysis exposed significant predictive relationships between the left rectus femoris activation and peak velocity in a cluster between 0.09 seconds before to 0.04 seconds after peak velocity. Indicating that the left rectus femoris was integral in the production of peak boat velocity during both left and right paddle strokes.

Both the left and right rectus abdominus activation displayed significant correlations with peak

Table 4.12. Time line analysis of EMG Activity with mean velocity during the left paddle stroke.

Right Rectus Femoris	Left Rectus Femoris	Right Gastrocnemius	Left Gastrocnemius	Right External Oblique	Left External Oblique	Right Rectus Abdominus	Left Rectus Abdominus	Time
								0.10
								0.09
								0.08
								0.07
								0.06
								0.05
								0.04
								0.03
								0.02
								0.01
								Peak
								0.01
							■	0.02
						■	■	0.03
						■	■	0.04
						■ *	■	0.05
						■ *	■	0.06
			■			■ *	■	0.07
						■ *	■	0.08
						■ *	■ *	0.09
						■ *	■	0.10
						■	■	0.11
							■	0.12
	■ *				■		■	0.13
	■ *				■			0.14
	■ *				■			0.15
	■ *				■			0.16
	■ *			■	■			0.17
	■ *			■	■			0.18
	■ *			■	■			0.19
	■ *			■	■			0.20
	■ *			■	■			0.21
	■ *			■	■			0.22
	■ *			■	■			0.23
	■ *				■			0.24
	■ *							0.25

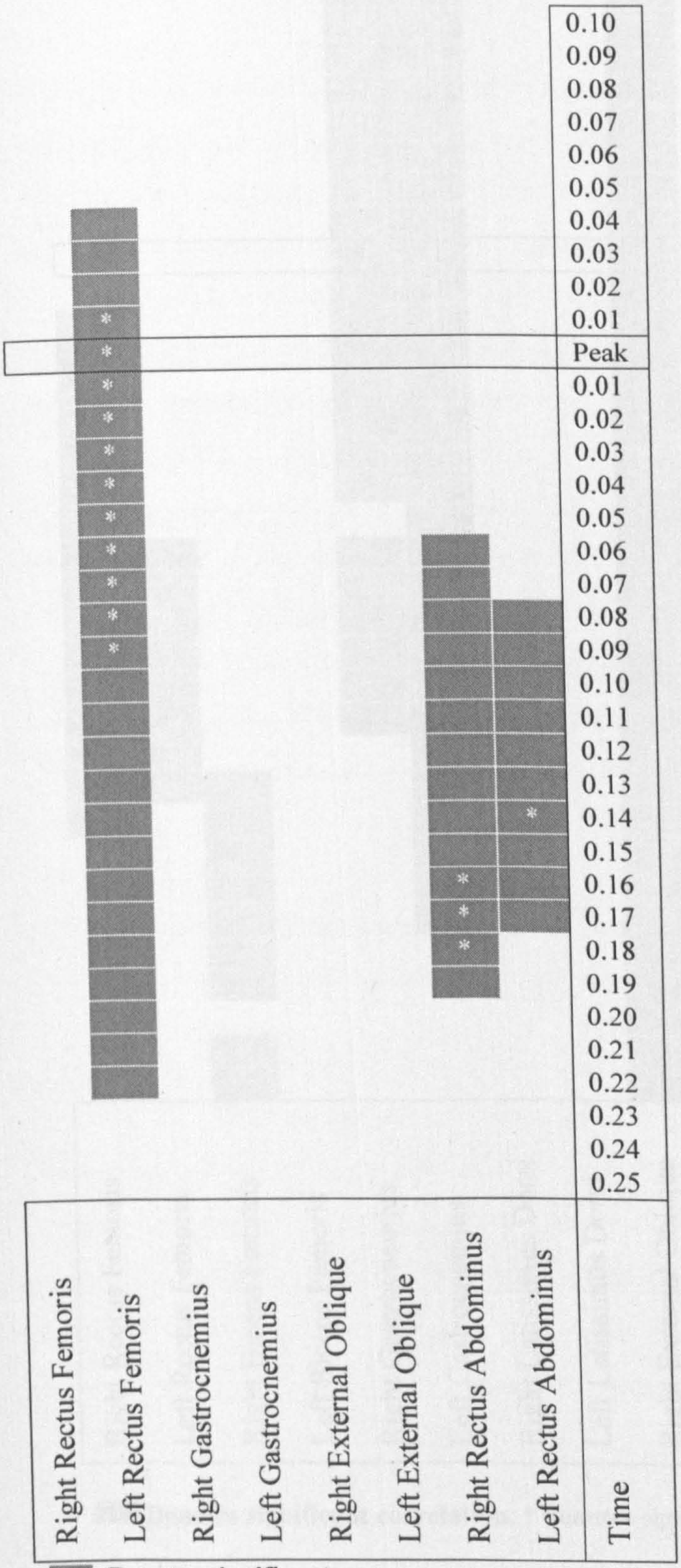
■ Denotes significant correlation, * denotes significant predictive relationship

velocity; however the LRA displayed greater significance within the right paddle stroke. The significant correlations displayed a cluster from 0.18 seconds to 0.9 seconds before peak velocity as the level of activation increased, however as the activation reached peak the correlations became non significant.

Investigation of the relationship between the muscular activation and the mean boat velocity identified a number of clusters of significant correlations. During the left paddle stroke (table 4.12) the left rectus femoris displayed an identical cluster to that observed with peak velocity, with significant predictive relationships with mean velocity from 0.25 seconds to 0.13 seconds before peak velocity. Thus coinciding with extension of the left knee at the end and beginning of the catch and power maintenance phase respectively. This provides further support to the link between left rectus femoris activation and boat velocity.

The external obliques displayed similar clusters of significant correlations with mean velocity as with peak velocity during the early part of the left paddle stroke. These clusters again occurred simultaneously with the left rectus femoris during the power maintenance and end of the catch phase. The relationship between mean velocity and activation of the right rectus abdominus exhibited an increase in the cluster of significant correlations

Table 4.13. Time line analysis of EMG activity with mean velocity during the right paddle stroke.



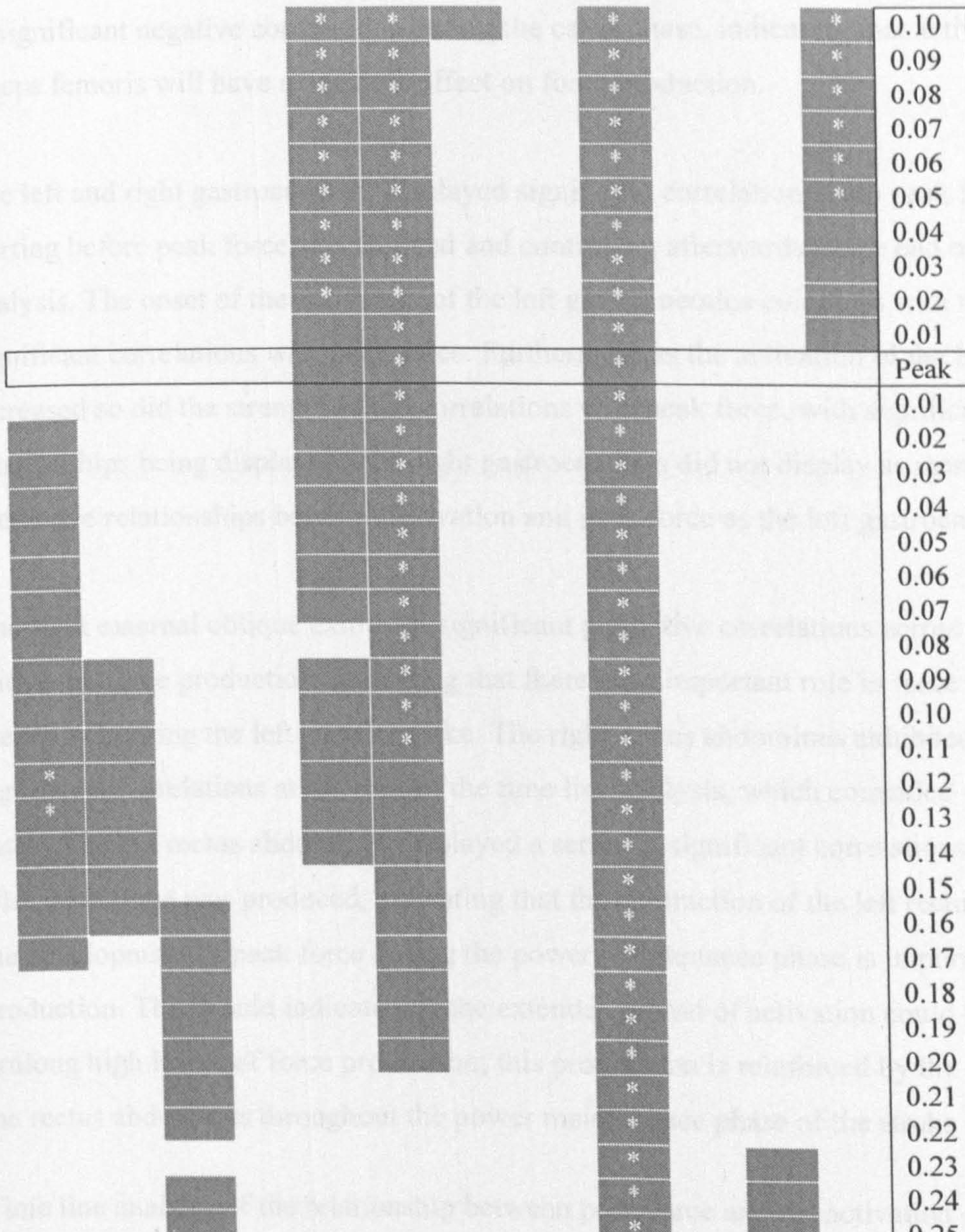
Denotes significant correlation, * denotes significant predictive relationship

ranging from 0.11 seconds to 0.03 seconds before peak velocity. Moreover the left external oblique displayed a cluster of significant correlations with mean velocity simultaneously with the right, coinciding with the increase in activation levels during the power maintenance phase.

Analysis of the interactions between mean velocity and muscular activation during the right stroke (table 4.13) exhibited similar findings to those presented between peak velocity and muscular activation. The cluster of significant correlations in the left rectus femoris coincided with the decline in muscular activation and as the knee moves away from the point of greatest flexion. Alongside the cluster within the left rectus femoris, further clusters were displayed between the mean velocity and the left and right rectus abdominus. The clusters of significant correlations coincided with the increase in muscular activation just before the mid-point of the stroke during the power maintenance phase.

Significant correlations and relationships between peak force and muscular activation during the left paddle stroke are presented in table 4.14. The right rectus femoris displayed a cluster of correlations with

Table 4.14. Time line analysis of EMG activity with peak force during the left paddle stroke.



Denotes significant correlation, * denotes significant predictive relationship

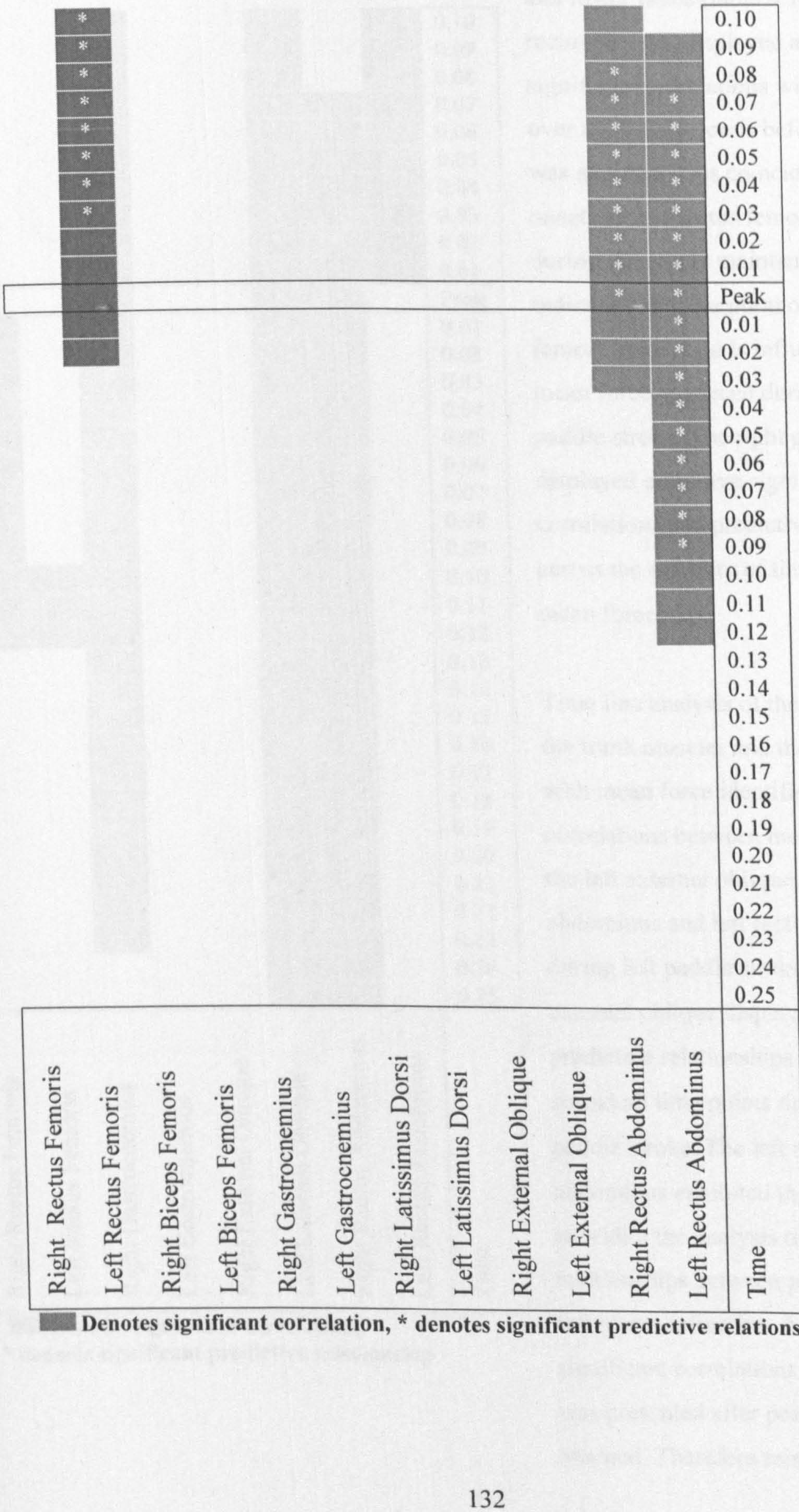
peak force as the force increased during the power maintenance phase as the right hip flexed, providing support to the importance of the rectus femoris in flexing the hip established during the technique analysis. The left rectus femoris displayed a similar cluster to the right, with a series of significant correlations occurring from 0.16 seconds to 0.09 seconds before peak force as the left knee moves toward its maximal extension. The right biceps femoris displayed a series of significant negative correlations during the catch phase, indicating that activation in the biceps femoris will have a negative effect on force production.

The left and right gastrocnemius displayed significant correlations with peak force production starting before peak force was attained and continuing afterwards to the end of the time line analysis. The onset of the activation of the left gastrocnemius coincides with the start of the significant correlations with peak force. Furthermore as the activation of the left gastrocnemius increased so did the strength of the correlations with peak force, with significant predictive relationships being displayed. The right gastrocnemius did not display as many significantly predictive relationships between activation and peak force as the left gastrocnemius.

The right external oblique exhibited significant predictive correlations across all time points with peak force production, indicating that there is an important role in force production from the REXO during the left paddle stroke. The right rectus abdominus exhibited a small cluster of significant correlations at the start of the time line analysis, which coincided with the end of the catch. The left rectus abdominus displayed a series of significant correlations with peak force after peak force was produced, indicating that the contraction of the left rectus abdominus after the development of peak force during the power maintenance phase is important in force production. This would indicate that the extended period of activation could be in an attempt to prolong high levels of force production; this proposition is reinforced by the clear activation of the rectus abdominus throughout the power maintenance phase of the stroke (figure 4.22).

Time line analysis of the relationship between peak force and the activation of the trunk and leg muscles identified significant correlations with the left rectus femoris, and the left and right rectus abdominus during the right paddle stroke (table 4.15). The left rectus femoris displayed a series of significant correlation and predictive relationships with peak force starting just before peak force and continuing to 0.1s after peak force. Simultaneously the right rectus femoris displayed a similar cluster of significant correlations with peak force, indicating that as the right rectus femoris and rectus abdominus increase in the magnitude of activation force production will increase. The left rectus abdominus displayed a cluster of significant correlations with peak force during the right paddle stroke from 0.12 seconds before to 0.09 seconds after peak force. These relationships were driven by the increase in activation as the force developed with the peaks occurring within close proximity.

Table 4.15. Time line analysis of EMG activity with peak force during the right paddle stroke.



Denotes significant correlation, * denotes significant predictive relationship

Table 4.16. Time line analysis of EMG activity with mean force during the left paddle stroke.

Right Rectus Femoris	Left Rectus Femoris	Right Gastrocnemius	Left Gastrocnemius	Right External Oblique	Left External Oblique	Right Rectus Abdominus	Left Rectus Abdominus	Time
		■ *			■ *		■ *	0.10
		■ *			■ *		■ *	0.09
		■ *			■ *		■ *	0.08
		■ *			■ *	■	■ *	0.07
		■ *			■ *	■	■ *	0.06
		■ *			■ *	■	■ *	0.05
		■ *			■ *	■	■	0.04
		■ *			■ *	■ *	■	0.03
		■ *			■ *	■ *	■	0.02
		■ *			■ *	■ *	■	0.01
		■ *			■ *	■ *		Peak
■		■ *			■ *	■ *		0.01
■		■ *			■ *	■ *		0.02
■		■ *			■ *	■ *		0.03
■		■ *			■ *	■ *		0.04
■		■ *			■ *	■ *		0.05
■		■ *			■ *	■ *		0.06
■		■ *			■ *	■ *		0.07
■		■ *			■ *	■ *		0.08
■		■ *			■ *	■ *		0.09
■	■	■ *			■ *	■ *		0.10
■	■	■ *			■ *	■ *		0.11
■	■	■ *			■ *	■ *		0.12
		■ *			■ *	■ *		0.13
		■ *			■ *	■ *		0.14
		■ *			■ *	■ *		0.15
		■ *			■ *	■ *		0.16
		■ *			■ *	■ *		0.17
		■ *			■ *	■ *		0.18
		■ *			■ *	■ *		0.19
		■ *			■ *	■ *		0.20
		■ *			■ *	■ *		0.21
		■			■ *	■ *		0.22
		■			■ *	■ *		0.23
					■ *	■ *		0.24
					■ *	■ *		0.25

■ Denotes significant correlation,
*** denotes significant predictive relationship**

Mean force development throughout the left paddle stroke exhibited significant correlations with muscles in the trunk and lower limbs (table 4.16). The right rectus femoris displayed a cluster of significant correlations with mean force over the 0.12 seconds before peak force was attained. This coincided with the onset of right rectus femoris activation during the power maintenance phase, indicating that the point of right rectus femoris activation is influential in the mean force produced during a left paddle stroke. The right gastrocnemius displayed extensive significant correlations and predictive relationships across the majority of time points with mean force.

Time line analysis of the activation of the trunk muscles and their relationship with mean force identified significant correlations between mean force and the left external oblique, right rectus abdominus and left rectus abdominus during left paddle strokes. The left external oblique displayed significant predictive relationships with mean force across all time points during the left paddle stroke. The left rectus abdominus exhibited the same pattern as within the analysis of the relationships between peak force and left rectus activation. A cluster of significant correlations with mean force was presented after peak force was attained. Therefore reinforcing the

Table 4.17. Time line analysis of EMG activity with mean force during the right paddle stroke.

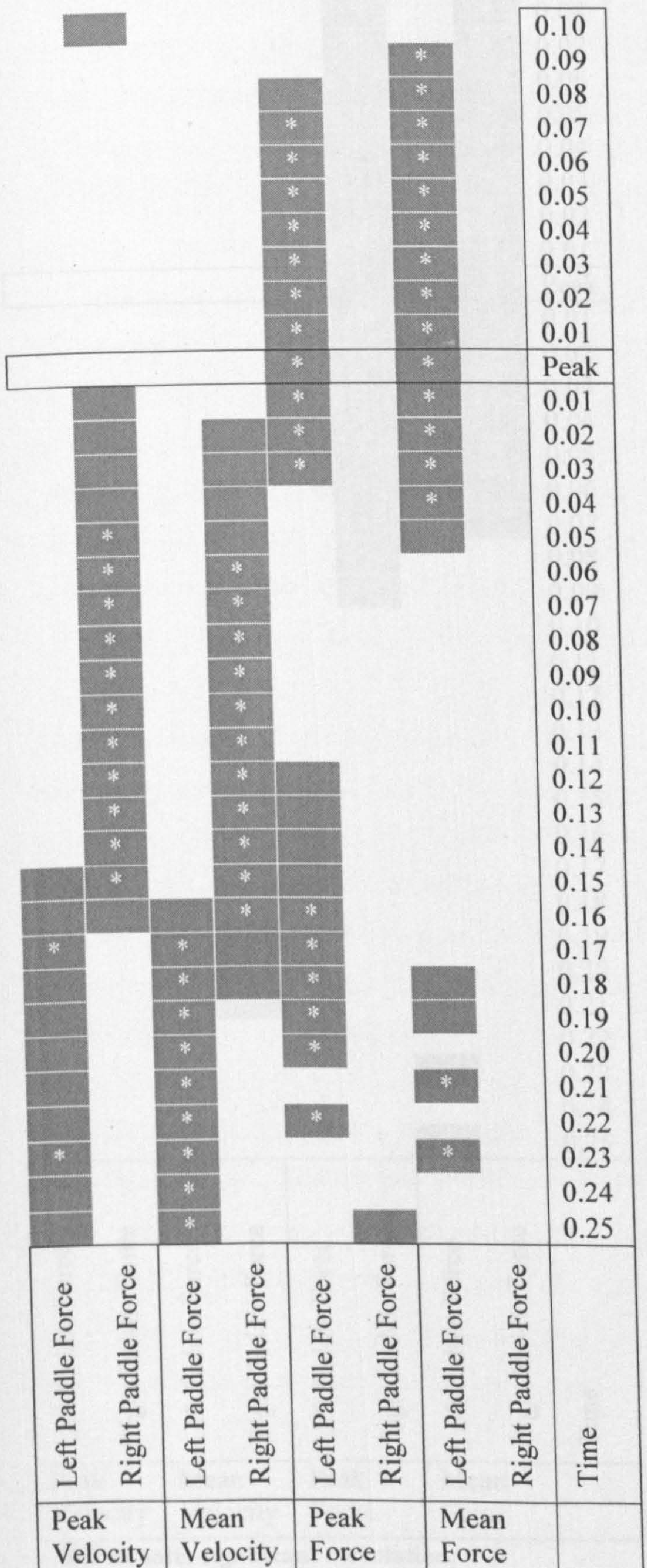
Right Rectus Femoris	Left Rectus Femoris	Right Gastrocnemius	Left External Oblique	Right Rectus Abdominus	Left Rectus Abdominus	Time
	■ *			■	■	0.10
	■ *			■	■	0.09
	■ *			■ *	■ *	0.08
	■ *			■ *	■ *	0.07
	■ *			■ *	■ *	0.06
	■ *			■ *	■ *	0.05
	■			■ *	■ *	0.04
	■			■ *	■ *	0.03
	■			■	■ *	0.02
	■			■	■ *	0.01
				■	■ *	Peak
				■	■ *	0.01
					■ *	0.02
					■ *	0.03
					■ *	0.04
					■ *	0.05
					■ *	0.06
					■ *	0.07
					■ *	0.08
					■ *	0.09
					■	0.10
					■	0.11
					■	0.12
						0.13
						0.14
						0.15
						0.16
						0.17
						0.18
						0.19
						0.20
						0.21
						0.22
						0.23
						0.24
						0.25

■ **Denotes significant correlation, * denotes significant predictive relationship**

suggestion that the contraction of the left rectus abdominus after peak force is developed has an important role in the production of both mean and peak force during a left paddle stroke. The right rectus abdominus displayed a much greater range of significant correlations across the majority of the left paddle strokes. Thus indicating that the right rectus abdominus has a greater relationship and therefore effect on the force production during the left paddle stroke. These findings provide further support for the suggestion that an extended period of activation in the rectus femoris was produced in an attempt to prolong high levels of force production.

The relationships between mean force produced during the right paddle stroke (table 4.17) and the activation of the trunk and leg muscles corroborated findings highlighted between the muscle activation and peak force. Significant correlations between mean force and the left rectus femoris occurred after peak force was produced. This was also identified to be true within the relationships between mean force and the right rectus abdominus. However the right rectus abdominus also displayed significant correlations with mean force at the point of peak force and shortly before. The left rectus abdominus displayed an extensive cluster of significant correlations starting 0.12s before peak force to 0.1s after. This cluster along with the findings from the

Table 4.18. Time line analysis of force production during the left paddle stroke.



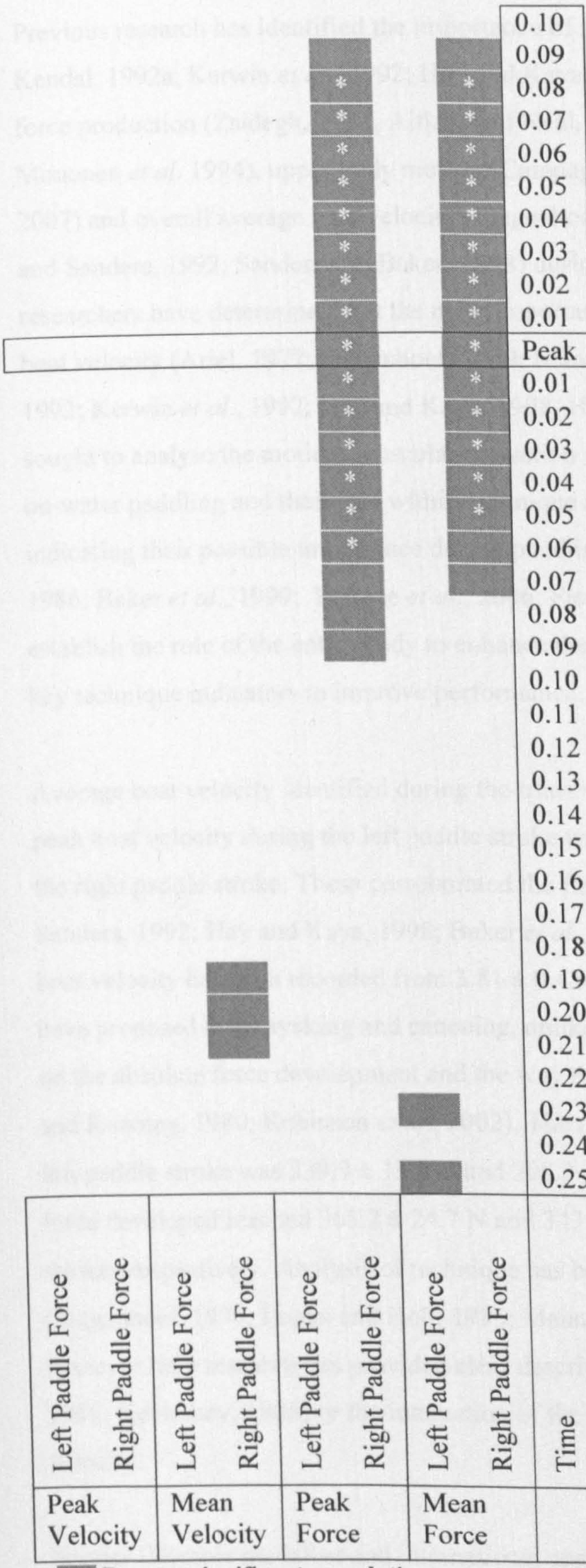
Denotes significant correlation, * denotes significant predictive relationship

left paddle stroke suggest that the contralateral rectus abdominus has an important role in the development of peak force and maintenance of mean force during the paddle stroke.

4.7.3.2. Paddle Force

During the left paddle stroke (table 4.18) the force produced at the left blade was significantly correlated with peak velocity from 0.25s to 0.15s before peak. This cluster of significances was also present between mean velocity and left blade force (0.25s to 0.16s before peak velocity). These clusters coincided with the time period in which subjects produced greatest force during the paddle stroke, therefore reinforcing the relationship established earlier between peak force and peak velocity during the left paddle stroke. An elongated cluster of significant correlations was evident between the force recorded at the right blade and mean/peak velocity during the left paddle stroke (0.16 to 0.05 seconds before peak). Further investigation identified that a significant negative predictive relationships existed, characterised by an increase in force resulting in a decrease in velocity. This finding conflicted with the

Table 4.19. Time line analysis of force production during the right paddle stroke.



Denotes significant correlation,
*** denotes significant predictive relationship**

theory that the peaks in force recorded at the contralateral paddle would be beneficial in aiding force production, proposed during the technique analysis. The peak and mean force displayed clusters of significance with the force produced at the left paddle clustering around the point of peak force. This pattern was mirrored in the right paddle stroke with clusters between peak and mean force and right paddle force production.

During the right paddle stroke the force produced at the right paddle displayed no significant relationships with peak or mean velocity; furthermore the negative relationship identified between force recorded in the contralateral blade during the left paddle stroke was not presented during the right paddle stroke (table 4.19).

4.8. Discussion

Previous research has identified the importance of stroke rate (Plagenhoef, 1979; Sanders and Kendal, 1992a; Kerwin *et al.*, 1992; Hay and Kaya, 1998), stroke length (Hay and Kaya, 1998), force production (Zsidegh, 1981; Aitken and Neal, 1992; Mononen and Viitasalo, 1995; Mononen *et al.* 1994), upper body motion (Campagna *et al.*, 1982 and 1987; Fleming *et al.*, 2007) and overall average boat velocity (Plagenhoef, 1979; Mann and Kearney, 1980; Kendal and Sanders, 1992; Sanders and Baker, 1998) during flat-water sprint kayaking. The majority of researchers have determined that the most important measure of performance being the average boat velocity (Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980; Kendal and Sanders, 1992; Kerwin *et al.*, 1992; Hay and Kaya, 1998; Hay, 2002). However no research to date has sought to analyse the motion, muscular activation and contribution of the trunk and legs during on-water paddling and their role within technique as a whole, despite a number of researchers indicating their possible importance during paddling (Mann and Kearney, 1980; Kemecsey, 1986; Baker *et al.*, 1999; Pertone *et al.*, 2006; Fleming *et al.*, 2007). Therefore it is important to establish the role of the entire body to enhance the understanding of performance and provide key technique indicators to improve performance.

Average boat velocity identified during the trials was 4.78 ± 0.45 m.s^{-1}, while the intra stroke peak boat velocity during the left paddle stroke was 5.25 ± 0.48 m.s^{-1} and 5.23 ± 0.53 m.s^{-1} for the right paddle stroke. These corroborated the findings of previous research (Kendal and Sanders, 1992; Hay and Kaya, 1998; Baker *et al.*, 1999; Kerwin *et al.*, 1992) in which average boat velocity has been recorded from 3.81 ± 0.45 m.s^{-1} to 5.41 ± 0.52 m.s^{-1}. Other researchers have proposed that kayaking and canoeing, unlike other water sports, has a critical dependency on the absolute force development and the way that it is developed (Plagenhoef, 1979; Mann and Kearney, 1980; Robinson *et al.*, 2002). The mean force produced by the paddlers during the left paddle stroke was 239.9 ± 13.5 N and 208.3 ± 17.4 N during the right stroke, whilst peak force developed reached 365.2 ± 24.7 N and 343.6 ± 43.1 N during the left and right paddle strokes respectively. Analysis of technique has been conducted by a range of researchers (Plagenhoef, 1979; Logan and Holt, 1985; Mann and Kearney, 1980; Kerwin *et al.*, 1992), however little research has provided clear description of paddling technique (Logan and Holt, 1985; Kemecsey, 1986) or the interaction of the upper and lower body in relation to force and velocity.

Former Olympic medallist and international coach Imre Kemecsey presented a description of an ideal technique in a 1986 manuscript against which comparisons will be drawn. Results from the analysis of all paddlers indicated both contrasting and corroborative findings, with the upper limbs supporting the technique proposed by Kemecsey (1986). The data for ipsilateral, referring to the side of blade entry, elbow and shoulder angles during the catch supported the extended and flexed positions, respectively, outlined by Kemecsey (1986), assisting in an increased forward reach and therefore a longer stroke. Further support was provided with the trunk displaying a rotated position to the ipsilateral side, while the flexed position of the hip offered further corroboration of Kemecsey's (1986) technique. The key difference between Kemecsey's (1986) technique and the observed technique of the paddlers was the motion of the knee, with the knee extending throughout the catch phase caused by a contraction of the rectus femoris, instead of holding a flexed position (figure 4.29).

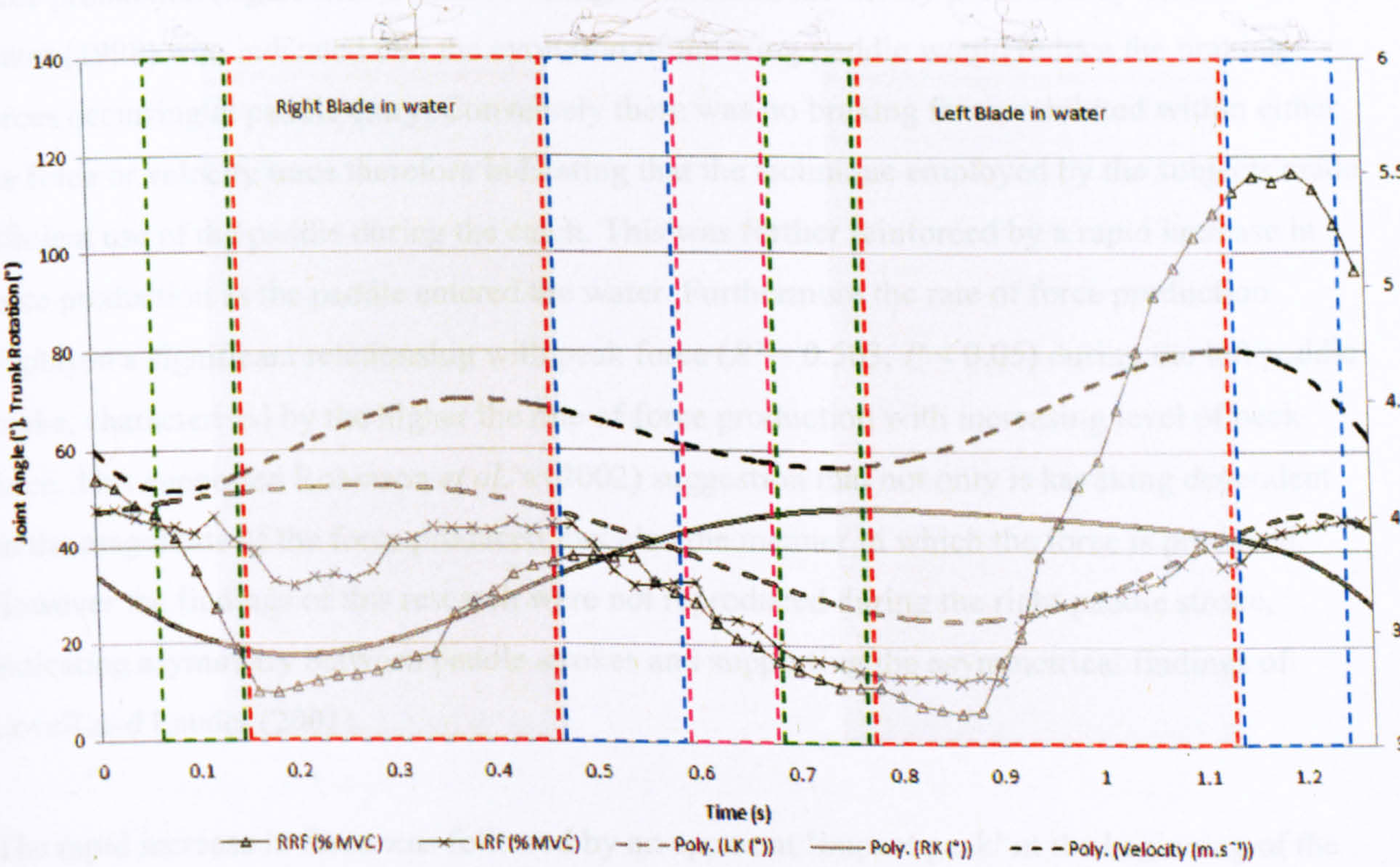


Figure 4.29. A representative data trace of the subject group displaying rectus femoris activation, knee flexion and kayak velocity during a single stroke cycle.

The contralateral side of the body displayed similar support to Kemecsey's (1986) technique with the shoulders, elbows, trunk and hips all supporting the proposed 'ideal' technique. The contralateral knee, as on the ipsilateral side displayed a conflicting finding as it flexed throughout the catch phase before holding position at the end of the phase. Furthermore the flexion of the knee coincided with an extensive activation of the gastrocnemius indicating that the gastrocnemius is the prime mover of knee flexion. This is further reinforced by limited activation in the rectus femoris and biceps femoris and the dorsiflexed position of the ankles, identified by Logan and Holt (1985), when the feet are in contact with the foot plate. These findings are in direct conflict with the results of Logan and Holt (1985) who identified contractions in both the rectus femoris and biceps femoris, whilst recording no activation in the lateral head of the gastrocnemius during the catch phase; however the data collected by Logan and Holt (1985) was derived from on-ergometer paddling. This would indicate that the patterns of muscular activation of the legs varies between on-ergometer and on-water paddling, as it has been previously identified that the patterns of activation can vary between the two paddling environments (Fleming *et al.*, 2007).

During the catch the reduction in boat velocity briefly reaches a plateau at its lowest level prior to paddle entry at which point velocity began to increase simultaneously with the increase in force production (figure 4.29). These findings reinforced the theory presented by Sanders and Baker (1998) who indicated that the evolution of the wing paddle would reduce the braking forces occurring at paddle entry. Conversely there was no braking force exhibited within either the force or velocity trace therefore indicating that the technique employed by the subjects made efficient use of the paddle during the catch. This was further reinforced by a rapid increase in force production as the paddle entered the water. Furthermore the rate of force production displayed a significant relationship with peak force ($R^2 = 0.503$, $P < 0.05$) during the left paddle stroke, characterised by the higher the rate of force production with increasing level of peak force. This supported Robinson *et al.*'s (2002) suggestion that not only is kayaking dependent on the magnitude of the force produced, but also the manner in which the force is produced. However the findings of this research were not reproduced during the right paddle stroke, indicating asymmetry between paddle strokes and supporting the asymmetrical findings of Lovell and Lauder (2001).

The rapid increase in force was followed by an apparent 'impact peak' at the beginning of the power maintenance phase, similar to that found in a running ground reaction force trace (see figure 4.21), though the distinctiveness of the peak varied between strokes. This 'impact' peak indicates a 'slapping' entry of the paddle against the water during entry, which coaches identify as a flaw within paddling technique; however this does not appear to have caused any detrimental braking forces. Motions of the whole body during the power maintenance phase demonstrated further conflict between the observed trends of motion and those outlined by Kemecsey (1986). The motion of the trunk exhibited some support for Kemecsey's (1986) technique during both the left and right paddle stroke, with motion of the thoracic region displaying a contralateral rotation in accordance with Kemecsey (1986). However, during the right paddle stroke all subjects exhibited a rotation in the lumbar region toward the ipsilateral side, coinciding with an increase in the activation of the right external oblique. This would indicate that the thoracic and lumbar spine rotate independently of each other in contrasting directions, possibly as a way of ensuring boat stability. This trend was identified at the beginning of the left paddle stroke; however as the subjects moved trough the stroke the thoracic and lumbar spine motion became more similar in nature. The greater coordination between the spinal regions of the trunk during the left paddle stroke appear to have created a more efficient stroke as significantly higher mean force (left: 239.9 ± 13.5N, right: 208.3 ± 17.4N, $P > 0.05$), higher peak force (left: 365.2 ± 24.7N, right: 343.6 ± 43.1N) and marginally higher peak intra stroke velocity (left: 5.25 ± 0.48 $m.s^{-1}$, right: 5.23 ± 0.53$m.s^{-1}$) were observed during the left paddle stroke.

The ipsilateral elbow is another area of conflict between Kemecsey's (1986) technique and the observed technique, with Kemecsey (1986) outlining that the ipsilateral elbow should hold an extended position at the beginning of the power maintenance phase, helping to encourage a lateral motion of the paddle. There is limited support for this presented by the pattern of movement of the left elbow at the beginning of the left stroke; however this was characterised by a slow rate of flexion during the first 0.1 s of the stroke, before elbow flexion soon increased, while data traces from the right side identified a continuous flexion in the ipsilateral elbow throughout the power maintenance phase. The greater extension exhibited in the left elbow, in conjunction with higher force and velocity produced during the left stroke, would indicate that Kemecsey (1986) was correct and the elbow is required to hold greater extension at the beginning of the stroke to produce an efficient powerful stroke.

The knees did not support the technique proposed by Kemecsey (1986). The ipsilateral knee displayed extension early in the power maintenance phase, in agreement with Kemecsey's (1986) technique; however the ipsilateral knee reached full extension early in the power maintenance phase corresponding with the rapid increase in force production. The ipsilateral knee held the point of maximum extension for a short period before beginning to flex again as the activation of the ipsilateral gastrocnemius continued to increase through until the end of the power maintenance phase. The identification of the ipsilateral gastrocnemius exhibiting prominent activation as the ipsilateral knee flexed reinforced the theory that the gastrocnemius was the prime mover in the flexion of the knee.

The hips, both ipsilateral and contralateral supported the technique set out by Kemecsey (1986) with the contralateral rectus femoris presenting a prominent increase in activation levels coinciding with the flexion of the contralateral hip. This indicates that the rectus femoris has a prominent role in the flexion of the hip. Furthermore the ipsilateral rectus femoris displayed peaks of activation at the beginning and end of hip extension signifying that the rectus femoris plays a role in stabilising the body motion and therefore the kayak at the beginning and end of the hip extension. Furthermore this could indicate that the muscles of the lower leg if not causing the motion are utilised to keep a tension within a solid base across which the paddler can produce force. This provides support for the theory of tensegrity proposed by Kemecsey and Moll (1998), explained in the human body as bones acting as an internal compressor system, while the muscles and tendons provide tension that provides the system with local rigidity (Kemecsey and Moll, 1998).

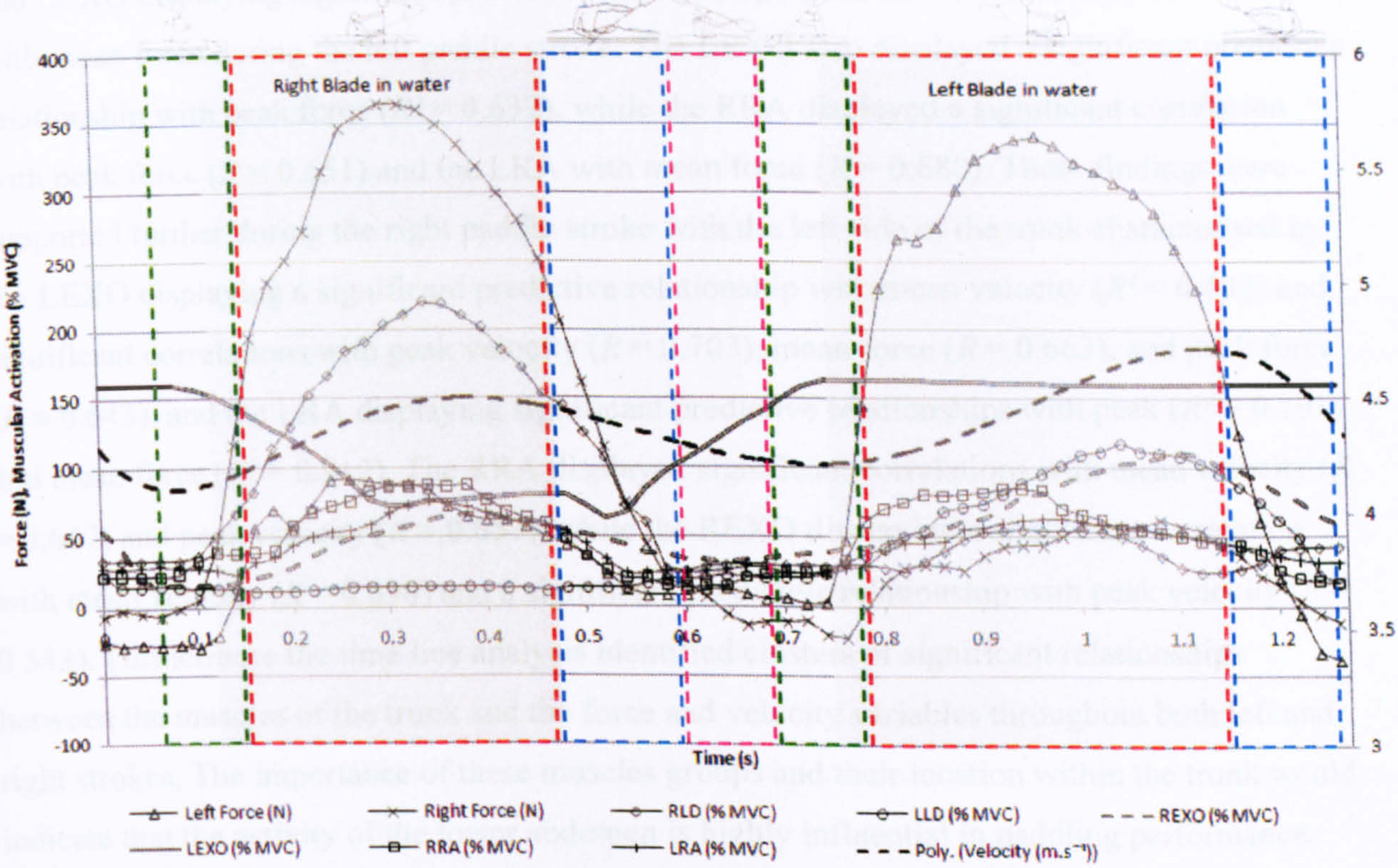


Figure 4.30. A representative data trace of the subject group displaying latissimus dorsi, external oblique, rectus abdominus, paddle force and kayak velocity during a single stroke cycle.

During the technique analysis of the power maintenance phase the importance of the trunk musculature began to be established, with the ipsilateral latissimus dorsi, rectus abdominus and external oblique, in conjunction with the contralateral rectus abdominus and external oblique all displaying peak activation alongside peaks in force and velocity production (figure 4.30). This suggests that these muscles have an important role in force production, the latissimus dorsi contributing to two interlinked motions. Firstly, and primarily, the extension of the shoulder as the paddle is moved backwards and secondly aiding in the rotation of the thoracic spinal region. The external obliques appear to have two roles within the paddle technique; the rotations of the trunk indicate that the ipsilateral external oblique is producing a concentric contraction causing the rotation of the spine. However the contraction of the contralateral external oblique during the stroke indicates that the secondary role may be an isometric/eccentric contraction. This type of isometric contraction was also identified in the rectus abdominus, both the ipsilateral and contralateral side, as clear activation was presented, however no flexion of the trunk was apparent. From these findings it can be theorised that the isometric contractions are producing a strong base and resistive force against which the force produced, resulting in the observed increased boat velocity.

The importance of the trunk muscles, more specifically the rectus abdominus and external obliques, was further reinforced within the findings of the statistical analysis, with peak RRA and LEXO displaying significant predictive relationships (RRA, $R^2 = 0.731$, LEXO, $R^2 = 0.642$) with mean force during the left paddle stroke. The LEXO also displayed a significant predictive relationship with peak force ($R^2 = 0.637$), while the RRA displayed a significant correlation with peak force ($R = 0.651$) and the LRA with mean force ($R = 0.680$). These findings were supported further during the right paddle stroke with the left side of the trunk characterised by the LEXO displaying a significant predictive relationship with mean velocity ($R^2 = 0.602$) and significant correlations with peak velocity ($R = 0.703$), mean force ($R = 0.663$), and peak force ($R = 0.643$), and the LRA displaying significant predictive relationships with peak ($R^2 = 0.891$) and mean force ($R^2 = 0.912$). The RRA displayed significant correlations with mean velocity ($R = 0.647$) and peak velocity ($R = 0.659$), while the REXO displaying a significant correlation with mean velocity ($R = 0.690$) and a significant predictive relationship with peak velocity ($R = 0.543$). Furthermore the time line analysis identified clusters of significant relationships between the muscles of the trunk and the force and velocity variables throughout both left and right strokes. The importance of these muscles groups and their location within the trunk would indicate that the activity of the lower abdomen is highly influential in paddling performance. Further evidence for this importance was identified by a significant negative predictive relationship established between lumbar range of rotation and boat velocity, characterised by the lower the range of lumbar rotation the higher the achievable speed. The combination of these corroborative findings has identified that a strong and stable lower trunk is important within the development of force and velocity. The identification of a stable lower trunk, in which the abdominal muscles display an isometric contraction causing tension within the lower abdomen, provides further support to Kemecsey and Moll's (1998) theory of applying tensegrity within the kayak stroke, as the strong stable trunk would allow for a more efficient production of force.

Rotation of the trunk is fundamental within technique required to correctly position the shoulder for the beginning of the catch, assist in extending the length of the stroke and allowing a clean paddle exit (Kemecsey, 1986). However the identification of a significant negative relationship between kayak velocity and lumbar spine rotation contradicts this theory. This indicates that trunk rotation should occur within the thoracic spine, which should therefore be important in paddling technique and therefore the production of force and velocity. Conversely, no significant relationships were established between thoracic motion and velocity or force production. From these conflicting findings it can be surmised that despite no empirical support the rotation within the thoracic trunk is imperative within technique and therefore the production of force and velocity.

The orientation of the paddle during the power maintenance phase has been previously identified to be important in the effective use of the wing blade. Sanders and Kendal (1992a) and Sanders and Baker (1998) indicated that to make efficient use of the paddle a vertical position should be held to ensure maximal force can be produced. The data collected did not support this theory with the vertical position being held only for a very short time period, which furthermore did not coincide with the point of peak force. The force peaked as the paddle started to move away from the vertical position, whist the time line analysis identified no significant correlations or predictive relationships between paddle orientation and either mean or peak force. Furthermore a significant relationship was established between the point at which the paddle was furthest from vertical and mean force ($R^2 = 0.504$, $P > 0.05$). Resultantly the vertical position of the paddle previously identified to be instrumental within technique may not be as important as previously indicated. Instead of focusing on a vertical paddle position paddlers should employ the technique expressed by Kemecsey (1986) in which the paddler moves around a 'fixed' paddle. This technique is characterised by the paddle entering at the catch after which the paddle will appear to stay in a 'fixed' position as the paddler pulls their body and the kayak past the paddle. This technique supports the brief vertical position identified in the data traces recorded.

Following the power maintenance phase, Kemecsey (1986) indicates that a 'popping' recovery occurs as the paddler rotates quickly toward the contralateral side to set the body for the next paddle stroke. A possible cause for the 'popping' recovery can be seen as the thoracic region continues to rotate toward the contralateral side until there is an abrupt change in direction of rotation back toward the ipsilateral side 0.04 s before the paddle exits the water. The abrupt change in direction of rotation back toward the ipsilateral side is apparent in both left and right stroke, which is followed by a full rotation to the contralateral side during the recovery and air work phases.

The contralateral rotation during the recovery phase is indicated by Kemecsey (1986) to cause a rotation along the longitudinal axis of the kayak, resultantly causing a reduction in boat velocity due to changes in the drag coefficient of the kayak. This was supported by the velocity and trunk rotation traces, as the boat velocity displayed a clear reduction as the lumbar region begins to rotate to the contralateral side. Further support for the technique proposed by Kemecsey

(1986) was identified in the angle of the elbows as the ipsilateral elbow reached maximal flexion during the recovery phase and the contralateral elbow slowly flexed throughout the phase. Further corroboration of Kemecsey's (1986) technique was provided by the contralateral hip and knee, both displaying little change in joint angle. The flexed position held by the contralateral hip coincided with activation of the contralateral rectus femoris reinforcing the theory that the rectus femoris plays an important role in the flexion of the hip and extension of the knee. The latter had further support provided by the interaction of ipsilateral knee extension and ipsilateral rectus femoris activation during the catch phase.

The ipsilateral hip and knee did not provide the same support to Kemecsey's (1986) theory of the recovery phase. Conversely the ipsilateral knee displayed a reduced rate of flexion throughout the phase. This coincided with a peak in ipsilateral gastrocnemius activation, reinforcing the indication that the gastrocnemius is the prime mover in knee flexion during paddling technique. The ipsilateral hip continued the extension motion started during the power maintenance phase, which coincided with a prominent level of activation in the ipsilateral rectus femoris. Therefore indicating that the rectus femoris may be contracting eccentrically controlling the motion and maintaining tension within paddling technique.

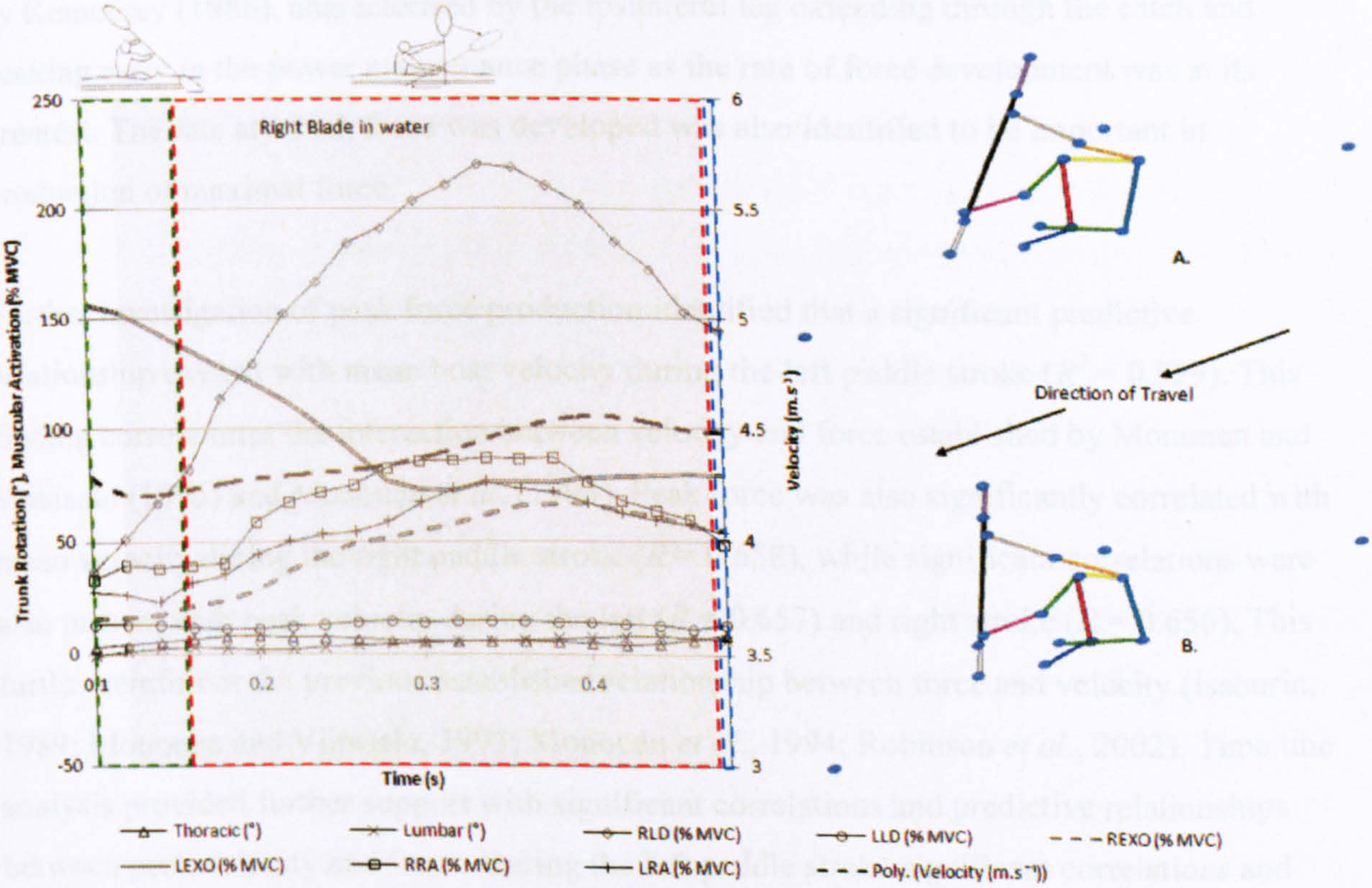


Figure 4.31. A representative data trace of the subject group displaying trunk rotation, latissimus dorsi, external oblique, and rectus abdominus activation and kayak velocity during the right paddle stroke, a). Depiction of the trunk position at the start of the power maintenance phase, b). Depiction rotation of the trunk and flexion of contralateral elbow as the paddler moves through the power maintenance phase, resulting in contralateral shoulder being at the preset flexion for blade entry.

The activation of the trunk muscles deteriorated during the last third of the power maintenance phase (figure 4.31) which continued though the recovery and reaching baseline levels during the air work, supporting the theory that the air work and recovery phases were used to prepare the subject for the contralateral stroke. This was further supported in the data traces of the contralateral shoulder, as the shoulder started to flex as the paddle was prepared for paddle entry (figure 4.31b). In addition, as the paddler enters the final air work phase the trunk continues to rotate, therefore continuing to cause a reduction in boat velocity corroborating Kemecsey's (1986) technique theory. Furthermore the relationship between the flexion in the ipsilateral knee and gastrocnemius continued to be exhibited, reinforcing that the gastrocnemius was the prime mover in knee flexion.

The technique comparison undertaken in relation to Kemecsey's (1986) technique highlighted that the motions of the upper body outlined by Kemecsey (1986) were clearly evident within the elite level subjects undertaking the testing protocol. The rotation of the trunk outlined by Kemecsey (1986) was also supported by the data collected, whilst further importance of the lower trunk was identified. The lower body displayed clear conflict with the technique outlined by Kemecsey (1986), characterised by the ipsilateral leg extending through the catch and peaking early in the power maintenance phase as the rate of force development was at its greatest. The rate at which force was developed was also identified to be important in production of maximal force.

Further investigation of peak force production identified that a significant predictive relationship existed with mean boat velocity during the left paddle stroke ($R^2 = 0.529$). This finding corroborates the interaction between velocity and force established by Mononen and Viitasalo (1995) and Mononen *et al.* (1994). Peak force was also significantly correlated with mean velocity during the right paddle stroke ($R = 0.658$), while significant correlations were also present with peak velocity during the left ($R = 0.657$) and right stroke ($R = 0.656$). This further reinforces the previous established relationship between force and velocity (Issourin, 1989; Mononen and Viitasalo, 1995; Mononen *et al.*, 1994; Robinson *et al.*, 2002). Time line analysis provided further support with significant correlations and predictive relationships between peak velocity and force. During the left paddle stroke significant correlations and predictive relationships were identified between left blade force at 0.25 seconds to 0.15 seconds before peak velocity during the left paddle stroke. This time period coincided with the increase in force production and as the force peaked. The cluster of significant correlations between left blade force and peak velocity was repeated with mean velocity during the left paddle stroke, though a greater number of significant relationships were exhibited. Findings from the right paddle stroke did not support these findings indicating no relationships between velocity and force production during the time line analysis. The non significant findings in the right paddle stroke may have resulted from a variation in timing of force peaks produced by each subject. This may have been caused by the opposing rotation of the thoracic and lumbar spine during the right paddle stroke. Additional predictive relationships were also identified between peak and mean force during the left (R^2 = 0.750) and right (R^2 = 0.929) paddle strokes. These predictive relationships were also established between peak and mean velocity (right stroke: R^2 = 0.961, left stroke: R^2 = 0.971).

A further series of significant correlations were exposed between peak and mean velocity and the force recorded at the right blade during the left paddle stroke. Subsequent regression analysis identified that the majority of the correlations displayed negative significant predictive relationships between the force recorded at the right paddle and peak/mean velocity during the left paddle stroke. These findings coincide with an increase in force displayed at the right blade during the left paddle stroke apparent in figure 4.21. This increase is also identifiable at the left blade during the right paddle stroke (figure 4.21) however time line analysis displayed no significant correlations or relationships. The reason for these readings will be due to the manner in which the force is determined, through the flexion of the paddle shaft; therefore a lateral force from the contralateral side during the paddle stroke would result in a positive force recording. This force could be a result of the paddler moving the paddle laterally during the stroke, indicating that it is not only the ipsilateral arm that guides the paddle. However due to the negative relationship established with velocity during the left paddle stroke and whilst during the right paddle stroke no firm relationship could be substantiated, therefore indicating that this lateral force from the contralateral arm during the paddle stroke should be avoided to ensure an efficient stroke and avoid negative effects on boat velocity.

As previously discussed the muscular analysis identified significant correlations and predictive relationships between the muscles of the trunk and force and velocity production. In addition to the trunk data, the peak activation of the left rectus femoris displayed significant correlations with mean (R = 0.670) and peak (R = 0.689) velocity during the left stroke. The left rectus femoris displayed further significant correlations with mean (R = 0.778, R^2 = 0.605) and peak (R = 0.751, R^2 = 0.6565) velocity and mean (R = 0.719, R^2 = 0.517) and peak (R = 0.806, R^2 = 0.650) force during the right paddle stroke, all of which displayed further significant predictive relationships. The identification of significant correlations and predictive relationships during both paddle strokes reinforces the proposed multiple role of the rectus femoris as the prime mover of hip flexion and knee extension, whilst providing stability during the stroke. However the right rectus femoris displayed no significant interaction with force or velocity production during the left or right paddle stroke.

Peak activation in the gastrocnemius displayed no significant correlations with velocity during either the right or left stroke, while the relationships with force production identified a significant correlation between mean force and peak right gastrocnemius activation and between peak left gastrocnemius activation and peak force during the left paddle stroke. With the left gastrocnemius displaying a negative significant predictive relationship with peak force during the left paddle stroke, signifying that the ipsilateral gastrocnemius could have negative effect on the production of peak intra stroke force. However as with previous findings significances were not supported during the contralateral stroke.

A number of the significant findings identified during an individual stroke have often not been corroborated by the contralateral stroke, creating possible questions concerning the validity of the findings. However the variations between left and right strokes should not produce concerns about the validity and reliability of the measures, conversely the disparity between the sides reinforces the asymmetrical findings of previous researchers (Kendal and Sanders, 1992; Kerwin *et al.*, 1992; Lovell and Lauder, 2001; Fleming *et al.* 2007). This asymmetry was further reinforced by the number of significant correlations between the independent variables and peak muscle activity during the left and right paddle stroke. The left stroke displayed nine significant correlations of which four displayed significant predictive relationships, whilst the right displayed fourteen significant correlations of which eight displayed further significance from the regression analysis. Within these significant findings the majority of the upper and lower muscles exhibited a significant relationship with either force or velocity during the paddle stroke; the exceptions to this were the biceps femoris and the latissimus dorsi. The biceps femoris displayed little activation throughout the stroke cycle and therefore the non significant findings were unsurprising, this however was not vindicated in the latissimus dorsi.

The latissimus dorsi displayed a monophasic pattern of activation, with the ipsilateral latissimus dorsi peaking shortly before peak force during the stroke. This finding is reinforced by Logan and Holt (1985) and Fleming *et al.* (2007) both of whom identified a monophasic pattern of activation in the ipsilateral latissimus dorsi. Further non significant findings were identified during the time line analysis with no correlation or relationships being established between the latissimus dorsi level of activation and either velocity or force. Despite the lack of statistically significant relationships between the activity of the latissimus dorsi and the independent variables it would be inappropriate to dismiss its importance within technique. It has been established by previous researchers that the latissimus dorsi displays prominent levels of activation and the nature of the motion required during technique would suggest an important role. Therefore despite no statistical findings linking levels of activation with force and velocity, the substantial levels of activation exhibited, with the support of previous research, would indicate that the latissimus dorsi has an important role within technique.

4.9. Conclusion

The understanding of the leg and trunk motion as part of the overall sprint kayaking technique has not previously been determined, despite acknowledgement from a number of researchers (Mann and Kearney, 1980; Logan and Holt, 1985; Petrone *et al.* 2006; Fleming *et al.* 2007) and coaches (Kemecsey, 1986) that they may have a prominent role. This provided an area that required investigation to provide important information to aid the understanding of paddling technique from which adaptations to the training techniques may evolve.

The analysis of the motions of the upper body and their interactions with the boat velocity and the force produced at the blade corroborated the majority of previous research. The mean and peak force and velocity values recorded coincided with what has been previously identified for international level paddlers while Mononen and Viitasalo (1995) and Mononen *et al.* (1994) identification of the relationship between the mean and peak force were generally reinforced. Therefore the first hypothesis can be accepted as a significant relationship does exist between boat velocity and force production. Previous research indicated that peak velocity force occurred simultaneously with a vertical paddle position (Sanders and Kendal, 1992a; Sanders and Baker, 1998), though findings from the current work identified a vertical paddle position prior to peak force and subsequently peak velocity. A further significant predictive relationship ($P < 0.05$) was identified between left elbow range of motion and mean kayak velocity. This relationship was characterised by an increased range of motion increasing mean kayak velocity during the left paddle stroke. All other joint angular measures, including maximal extensions and flexions and ranges of motion displayed no significant correlations or relationships with either force or velocity during the kayak stroke. As a result the fourth and fifth experimental hypotheses cannot be accepted with confidence, as little empirical support for these propositions was identified, despite technique analysis exhibiting general patterns of motion across all paddlers.

The levels of activation demonstrated by the muscles monitored in the trunk and legs indicate that they have roles of considerable importance within paddling technique. The peak activation of the left rectus femoris (LRF) displayed significant interactions with the majority of the dependent variables during the left and right paddle stroke, which was supported by a biphasic pattern of activation identified from the visual inspection. This indicated that the LRF had an important role in the stroke as it coincided with the flexion and extension of the knee as well as the force and velocity. However the right rectus femoris displayed no statistical relationship with either boat velocity or force, despite displaying a similar biphasic trend to the left rectus femoris. The conflict between the rectus femoris activation during the contralateral stokes provides two findings. Firstly reinforcing the asymmetrical nature of the kayaking stroke and secondly indicating that the rectus femoris has a multifunctional role within paddling technique, contributing to knee extension, hip flexion and stability during the paddle stroke.

Data traces identified that the gastrocnemius has an important role in the flexion of the knee at the end of the stroke, supported by negligible activation of the biceps femoris and the dorsiflexed position the ankles hold against the foot plate. While peak right gastrocnemius activation displayed a significant correlation with mean force during the left paddle stroke.

The latissimus dorsi was expected to display significant relationships with force and velocity as it has previously been identified to play a prominent role in paddling technique (Logan and Holt, 1985; Fleming *et al.*, 2007). However little significance was found between the latissimus dorsi and either the boat velocity or force production. This did not concur with the technique analysis which displayed a clear monophasic pattern of activation as researchers have previously identified (Logan and Holt, 1985; Fleming *et al.*, 2007). Furthermore the levels of activation exhibited by the latissimus dorsi indicated and the clear trend between force increase and increase in latissimus dorsi activation indicate that the latissimus dorsi has an important role within technique. Therefore despite the lack of statistically significant empirical evidence the latissimus dorsi has clear importance in paddling technique and subsequently force and velocity production.

It would appear it is the muscles of the lower trunk that play the most important role in paddling technique and performance. The rectus abdominus presented a biphasic activation trend across subjects interacting significantly with both paddle strokes. This was supported by statistical findings displaying a significant relationship with the force production and, when combined with the findings from study 1, it appears that the rectus abdominus has a resistive role producing a strong position against which the paddler can produce force, a trait also displayed sporadically in the external obliques. This was identified as the contralateral external oblique displayed significant correlations and regressions with force production during the paddle stroke. However the most important role the external obliques displayed was a significant relationship with the velocity and force production on the ipsilateral stroke side, causing a rotation of the trunk characterised by the ipsilateral shoulder moving backward.

The importance of a stable lower trunk was further emphasised by findings identified in the trunk motion. Rotations within the thoracic spinal region displayed no significant correlations or predictive relationship with either the force or velocity performance measures. However it can be summarised that rotation, which is fundamental in good technique (Kemecsey, 1986) and can be clearly identified during paddling, should occur within the thoracic region. This conclusion can be drawn as a significant negative predictive relationship was identified between lumbar region range of motion and velocity. This relationship, characterised by the lower the range of motion and the higher the attainable speed, coincides with the theory of having a strong base in the lower trunk supported by isometric contractions in the rectus abdominus and external oblique's resulting in an efficient production of force at the paddle, in a similar manner to that proposed by Kemecsey and Moll (1998) in the theories of tensegrity application.

It can be concluded that the motions and activation of the muscles of the trunk and legs display clear relationships with the velocity and force production, therefore the second and third experimental hypotheses can be accepted with confidence. Furthermore the interaction between the trunk, legs, upper limbs and paddle were characterised by the ipsilateral leg starting in a flexed position, with the trunk rotated so that the ipsilateral shoulder is ahead of the contralateral shoulder with greater rotation in the thoracic vertebrae, as the paddle is entered into the water. As the paddle is moved backwards the ipsilateral latissimus dorsi and the contralateral and ipsilateral rectus abdominus activate providing resistance against which force can be produced and the ipsilateral external oblique initiates a concentric contraction rotating the trunk moving the ipsilateral shoulder backwards. The ipsilateral knee moves toward peak extension shortly before peak force is reached, simultaneously the ipsilateral shoulder and elbow angles decreased as the paddle angle reaches vertical. As the force reaches peak shortly after the vertical paddle position, the ipsilateral knee continues to flex with the activation of the ipsilateral gastrocnemius increasing. At this point the ipsilateral latissimus dorsi peaks along with the rectus abdominus and the ipsilateral external oblique peaking shortly after as the trunk continues to rotate and the ipsilateral gastrocnemius activates. Then as the trunk reaches its maximal rotation to the ipsilateral side, the ipsilateral knee reaches its point of greatest extension, as the activation of the ipsilateral rectus femoris and then gastrocnemius peak. This pattern of interaction has been produced from both significant statistical findings and the analysis of technique, as the statistical analysis was conducted between the measured variables and dependent variables and not between all measured variables.

The key points to be extracted from this study are the latissimus dorsi, rectus femoris, gastrocnemius, external obliques and rectus abdominus display clear activation and therefore contribution during paddling, with the external obliques and rectus femoris displaying statistically significant positive relationships with the development of velocity and force during paddling. Furthermore electrotorsiometers and electrogonoimeters traces identified that there was considerable rotation of the trunk to the ipsilateral side and extension in the ipsilateral knee as the paddle was in contact with the water during the stroke and that the rotation of the trunk should occur in the thoracic spine as a statistically significant negative relationship was identified between range of lumbar spine rotation and velocity.

5. Thesis Discussion and Conclusions

5.1. General Discussion

Early research investigating sprint kayaking performance quickly identified average boat velocity to be the key performance measure resulting in extensive research examining ways in which average velocity can be improved. This led to an evolution in equipment design resulting in the transformation in the method of propulsion, resulting in further investigation into technique and the application of the new equipment. However, the interaction of the legs and trunk within kayaking performance had received little consideration, with only coaching texts by Kemecsey (1986) advocating these segments of the body being imperative within efficient technique. Only three previous studies (Mann and Kearney, 1980; Petrone *et al.*, 2006 and Fleming *et al.*, 2007) investigated any aspects of the understanding and contribution of these body segments. Petrone *et al.* (2006) investigating different types of seat and the effects on force production, trunk rotation and knee extension, while Fleming *et al.* (2007) was investigating the ability of the Dansprint kayak ergometer to reproduce on-water paddling technique. Mann and Kearney (1980) investigated the basic biomechanical parameters of on-water paddling, during which they determined the angle of the knees during paddling. However, the determination of the ankle joint had limited accuracy, resulting in a reduced accuracy in the determination of the knee angle. Therefore, although the findings identified measures and values of trunk rotation, leg extension and patterns of muscle activation there was no indication of the importance of the roles in paddling and therefore overall performance.

Initially, the notational analysis presented within this thesis, was undertaken to determine and reaffirm the important aspects of technique by differentiating between international, national and club ability level paddlers through a series of qualitative and quantitative measures. Results corroborated previous findings (Plagenhoef, 1979; Sanders and Kendal, 1992; Kerwin *et al.*, 1992; Hay and Kaya, 1998;) with the stroke rate differentiating between the international/national and club paddlers, however it did not prove to be sensitive enough to differentiate between the two more experienced groups despite the disparity in race times. Therefore further investigation into the propulsive and recovery phases of the stroke was conducted in an attempt to differentiate between international and national level paddlers. Results displayed no statistical significance in the percentage of the stroke time the international and national paddlers committed to the propulsive phase, therefore indicating that alternative factors distinguish international level paddlers. The results showed the international level paddlers to produce faster race times, contributed to by significantly short glide times, a wider paddle stroke, during which the paddle was entered further forward, with greater extension of the leg and an exaggerated rotation of the trunk. Furthermore there was a significantly smaller change in the forward lean and less unwanted boat motion presented by the higher ability paddlers.

Consequently it is clear that technique is directly linked to ability level therefore establishing that any further testing required should be undertaken with elite level athletes from which findings could be disseminated across all kayaking populations providing key performance markers for all levels of paddler to focus upon to increase their performance. More importantly the results identified that the trunk and legs appeared to have a clear relationship with ability level, characterised by greater use in more highly skilled paddlers. This reinforced the technique and coaching practices presented by former Olympic medallist Imre Kemecsey (1986), suggesting that more focus should be placed upon the larger muscle groups of the trunk and legs. From these findings it was therefore important to measure the motion and muscular activity of the trunk and legs. In addition to this, the interaction with the motions of the upper body needed to be established.

As previously noted (Mann and Kearney, 1980) the determination of the leg motion during on-water paddling poses problems in the identification of joint centres and motions, especially in the lower limbs, due to their positioning inside the kayak. This positioning therefore ruled out the use of kinematic analysis despite researchers such as Mann and Kearney (1980) attempting to do so. Therefore alternative methods of measuring the knee angle and the motion of the lower limbs was required. In attempts to overcome this issue a series of tests were undertaken, presented in chapter 4: Development of an On-water Movement Recording Protocols for Kayaking.

The analysis of sporting actions has been undertaken using a variety of techniques, including kinematics, kinetic, electromyography (EMG), and torsiometry. However, due to the water based environment of kayaking, analysis techniques have been limited to kinetic and kinematic analysis. Little previous research has incorporated the application of EMG within kayaking

(Logan and Holt, 1980; Fleming *et al.* 2007), with only Fleming *et al.* (2007) using electromyographical analysis on-water, whilst no previous research has utilised torsiometry in water based environment. The findings from the pilot work identified that the protocol employed was robust enough for testing, with only a minimal number of changes required. More specifically the protruding poles on the calibration frame required alterations to enhance the clarity of the markers, while a second torsiometer was required to allow analysis of the rotation throughout the spine at the thoracic and lumbar regions. In addition, the accuracy of the electrogoniometers were unit specific, while the application of the goniometers at the hip was compromised by the narrow cockpit. Therefore the two goniometers exhibiting the greatest accuracy were selected for use at the knee. Measurement of hip angle was conducted using an additional marker positioned on the lateral trunk 0.25m above the centre of the hip (judged as the greater trochanter) in conjunction with the thigh length from which trigonometry was utilised to determine the hip angle. As a direct result the camera position was required to be raised to ensure the knees were in camera view for the longest period of time. The final factor to arise from the development of the on-water analysis system was the synchronisation of the various measurement techniques, this was overcome through the use of key points during the paddle stroke and a data logger synchronization unit that transmitted and event spike through the EMG and electrogoniometer traces.

The finalised testing protocol, employed during the final study identified a number of significant relationships between the motions and muscular activity of the trunk and lower limbs and the boat velocity and force produced. Initially a significant relationship was established between boat velocity and force production, acknowledged to be the two key determinants of performance by many researchers (Ariel, 1977; Plagenhoef, 1979; Mann and Kearney, 1980; Campagna *et al.*, 1982; Logan and Holt, 1985; Campagna *et al.*, 1987; Kendal and Sanders, 1992, Kerwin *et al.* 1992; Sanders and Kendal, 1992; Mononen and Viitasalo, 1995; Mononen *et al.*, 1995; Sanders and Baker, 1998; Hay and Kaya, 1998; Baker *et al.*, 1999; van Someren, 2003; Petrone *et al.*, 2006; Fleming *et al.*, 2007). This finding, corroborated by Mononen and Viitasalo (1995) and Mononen *et al.*, (1995) assists in the explanation of the differences exhibited in the race times between international and national paddlers working at the same stroke rates presented in the notational analysis study. As a higher force production during the stroke would explain the faster race times achieved by the international paddlers.

Previously it has been suggested that a vertical paddle position coincided with peak velocity (Plagenhoef, 1979, Mann and Kearney 1980; Kerwin *et al.* 1992), this was clearly not the case from the findings. The vertical position of the paddle occurred shortly prior to peak force which was achieved prior to peak intra stroke velocity. Furthermore it has been suggested that the paddle should be positioned in a vertical position for as long as possible (Plagenhoef, 1979; Mann and Kearney, 1980; Sanders and Baker, 1998; Baker *et al.* 1999). However this was not identified in this research, conversely a vertical paddle angle was only achieved momentary before peak force. This indicates that the vertical position is not as important as vindicated within the literature. Conversely the findings supported the theory of the paddler moving around a 'fixed' paddle position promoted by Kemecsey (1986) allowing greater force transference.

The results from the current research echoed the majority of findings presented in the main body of research pertaining to the importance of the upper body within efficient technique. However the investigation of lower limb and trunk motion and muscular activation has uncovered several significant findings. The novel use of electrotorsiometers and electrogoniometers identified rotations of the trunk and changes in the knee angle. Technique analysis identified that the trunk rotation occurred predominantly in the thoracic region, characterised by the ipsilateral, referring to the side of blade entry, shoulder moving backwards during the stroke. The importance of this was reinforced by a significant negative relationship identified between lumbar spine range of motion and boat velocity, indicating that the rotation of the trunk needs to be produced in the thoracic spine to ensure no detrimental effect on velocity.

Coinciding with the ipsilateral rotation of the trunk the ipsilateral knee displayed an extension through the beginning of the stroke reaching the point of maximal extension early in the power/maintenance phase, supported by a clear activation of the rectus femoris. However investigation of the peak rectus femoris activation did not support this visual trend. Conversely findings indicated that the contralateral rectus femoris had a significant predictive relationship with force and velocity during the right paddle stroke. Therefore indicating that the rectus femoris has an important role in the production of force and velocity during the contralateral stroke. This was further corroborated in the identification of a biphasic pattern of activation across all subjects during the paddling cycle. This was not supported during the left paddle stroke; however this may be the result of the asymmetrical nature of paddling technique.

The gastrocnemius displayed no interaction with the velocity of the kayak, whilst the peak activation of the left gastrocnemius displayed a significant relationship with peak force during the ipsilateral stroke, exhibiting a peak coinciding with the activation of the left rectus femoris and activation coinciding with flexion of the knee. This indicates that the gastrocnemius causes the flexion of the knee and the rectus femoris flexion of the hip. However analysis of the peak activation of the right gastocnemius displayed significant correlation with the mean force during the contralateral paddle stroke reinforcing the asymmetrical nature of technique. The final muscle of interest in the leg, the biceps femoris, displayed no statistical significance with either velocity or force and furthermore visual inspection identified little activation within the muscle, from which it can be summarised that the biceps femoris has no importance in the production of force and has no contributory properties toward boat velocity.

The muscles of the trunk displayed much clearer interaction with the development of force and boat velocity. The first study identified that the international paddlers held the trunk position more consistently than the club and national paddlers, whilst also displaying less forward lean than the club paddler. This would indicate that the muscles of the trunk were active to hold the trunk in position. The rectus abdominus activation during on-water paddling displayed a biphasic pattern of activation, with prominent peaks occurring with both contralateral and ipsilateral paddles strokes. The peak right rectus abdominus activation displayed significant correlations with peak and mean velocity during the right paddle stroke, while significant correlations were also presented between the peak right rectus abdominus activation and mean and peak velocity during the left and right strokes. In relation to force however the peak and mean activation of the right rectus abdominus displayed significant correlations with peak force and significant predictive relationships with mean force during the left paddle stroke. This reinforced the trends identified from the technique analysis. This was provided with further support as the peak activation of the left rectus abdominus displayed significant predictive relationships with mean and peak force during the right paddle stroke and correlations were presented with the mean and peak force production during the left paddle stroke.

These significant findings were further reinforced through the time point analysis with the right rectus abdominus and left rectus abdominus displaying significant correlations and predictive relationships. From these findings it is clear that the rectus abdomnius plays an essential role within paddling, contributing greatly to velocity. Furthermore significant relationships with the mean and peak force variables were identified, indicating that the rectus abdominus contributes to the two key determinants of performance. These findings in conjunction with the lack of change identified in the forward lean (identified in the notational analysis) would indicate that the rectus abdominus has a largely isometric role during paddling. The isometric contraction of the rectus abdominus combined with the significant negative relationship between lumbar spine range of motion and velocity indicate that the lower trunk needs to be held in a stable strong position. This position will provide two important roles, firstly a strong resistive base from which the paddler can produce force and secondly act as a conduit for efficient transfer of force from the blade to the kayak in line with the principles of tensegrity (Kemecsey and Moll, 1998).

The results for each external oblique muscle differed, with the peak activation of the right external oblique displaying a significant correlation with mean velocity and a significant predictive relationship with peak velocity during the right paddle stroke, however displaying no other significant correlations or regressions with force. The peak activation of the left external oblique displayed significant predictive relationships with the mean and peak force during the left paddle stroke and with mean velocity during the right paddle stroke. The left external oblique also displayed significant correlations with peak velocity and force and mean force during the right paddle stroke. These significant findings indicate that the LEXO has an important role in the production of force, which as previously identified will have a direct effect on the velocity achieved. The anatomical role of the external obliques is rotation of the trunk, however the significant correlations and regressions identified in the contralateral external oblique during the paddle stroke would suggest that there is a secondary role. It can be therefore suggested that there may be a resistive role coinciding with the activation of the rectus abdominus against which the paddler produces paddle force. This was further supported by an identification of significant clusters of right external oblique activation with mean and peak velocity during the left paddle stroke. Therefore again reinforcing the proposal that the lower trunk needs to be held in a stable strong position to ensure effective force production and transfer.

Analysis of the latissimus dorsi activity was expected to reveal a significant relationship with force and velocity due to the rotation of the thoracic trunk, however this was not identified. Technique analysis identified a monophasic pattern of activation within the latissimus dorsi as a general trend, similar to Fleming *et al.* (2007). The time line analysis identifed a solitary significant correlation between the right latissimus dorsi and peak force at 0.1s after peak force was attained. No other significant relationships were exhibited therefore the latissimus dorsi has no statistically significant relationship to the production of force or boat velocity. Despite no significant statistical relationship existing with force or velocity, the high levels of activation recorded, supported by previous research (Fleming *et al.*, 2007; Logan and Holt 1980); indicated that the latissimus dorsi was important within technique. The role of which appears to coincide with the production of force at the paddle, although the exact contribution cannot be described empirically.

5.2. Implications

Substantial research into the flat-water kayaking stroke and race performance has been conducted however still questions remained to be answered. The importance of the legs and trunk within an effective stroke was one of these questions still to be resolved. Findings from this research have gone some way to explain the questions surrounding the application of these body parts, with results displaying significant use of the legs (rectus femoris and gastrocnemius) and trunk (rectus abdominus and external obliques) further corroborated by a general trend in the actions on these body parts.

From the results presented key indicators for performance identified in chapter 3 provide technique markers on which coaches and paddlers of club and national level paddlers can focus to improve performance. Focusing on increasing the width of the stroke, encouraging a greater forward reach to move the point of paddle entry forward, therefore increasing the water contact time and the distance over which propulsive force can be produced will aid in increasing average boat velocity and therefore performance. Results identified in chapters 3 and 5 indicated the importance of the legs and trunk for paddlers of all ability levels, providing lower ability paddlers with a technique component to enhance and develop.

In addition to supporting the development of lower ability paddlers, the findings provide elite international kayakers, in conjunction with their coaches empirical evidence to support alterations in paddling and training techniques. More specifically training techniques could be altered to include isometric muscular contractions and action specific weight training exercises for the trunk and lower limbs. Therefore increasing the strength of the pertinent muscle groups and consequently the propulsive forces that can be produced during paddling. Furthermore the identification of lumbar rotation having a detrimental effect on velocity provides a technique marker that paddlers should focus on. Paddlers and coaches should emphasise and improve rotation in the thoracic spine while limiting motion in the lumbar spine. The combination of these factors may result in increased average boat velocity and improved race performance.

5.3. Limitations of Research

The current research was limited similarly to Kerwin *et al* (1992) by the positioning of the high speed video cameras. Positions on the same side of the regatta lake resulted in estimation of several body markers occasionally at intervals during the digitisation process. This may have effected some of the joint angle data determined from the analysis.

Furthermore the application of simple linear regression analysis with such a small number of subjects (n = 8) could be seen as an improper use of such a statistical method. The effects of this were minimised by ensuring normal distribution and utilising Log10 transformation techniques to correct any skewed data sets. Moreover results from correlations, including the significance, run on the data have been presented and discussed alongside the results identified from the regression analysis. Furthermore the eight subjects participating in the study represent around 60-70% of the elite level kayak paddler population in Great Britain and therefore are an excellent representation of elite paddling technique.

5.4. Recommendations for Future Research

The current research in addition to the vast body of previous literature has identified the importance of an efficient stroke to maintain a high average boat velocity (Plagenhoef, 1979; Mann and Kearney, 1980; Kendal and Sanders, 1992; Sanders and Baker, 1998; Hay and Kaya, 1998; Baker *et al.* 1999), with the upper body controlling the fine motions of the paddle during the propulsive stroke and the recovery. Furthermore the importance of force production and its relationship to velocity has been reaffirmed after initial identification by Mononen and Viitasalo (1995) and Mononen *et al.* (1995).

The current research has answered an important question as to the role and interaction of the trunk and lower limbs in the flatwater kayak stroke, however one key area still requires investigation. This concerns the manner and efficiency in which forces produced at the blade are transferred through the paddler on to the kayak. The paddler has only two points of contact with the kayak at which the propulsive forces can be transferred to the foot plate and the seat. Therefore it is these areas that should be the focus for further investigation, using force analysis to compare the magnitudes and variations between the force transferred and the propulsive forces produced at the blade, with further investigation into the efficiency of the transfer.

5.5. General Conclusions

The focus of this research was to identify the importance of the trunk and lower limbs in the development of force and ultimately, the production of boat velocity. Each of the individual chapters have provided significant insight into the techniques employed in flatwater sprint kayaking.

The notational analysis confirmed the importance of the lower limbs and trunk with the international paddlers techniques displaying much greater use of these body segments. Furthermore the importance was reconfirmed as a general trend displayed that as the competitive level increased so did the application and motion of these parts of technique. This provided empirical evidence for the rationale of investigating these factors further.

The decision made to use a large final study instead of a series of small studies has resulted in an effective and efficient investigation of technique, the novel collaborative use of kinetic, kinematic, electromyography, electrogoniometry and electrotorsiometry techniques, has resulted in a comprehensive analysis across which comparisons and relationships have been established that would not have been possible in a series of short investigations. However, a number of obstacles were presented in the measurement of technique, as this approach had never previously been attempted.

The pilot work undertaken was required to develop an efficient and all encompassing protocol for the assessment of the paddling technique including the upper limbs, trunk and lower limbs, thus providing a full picture of paddling performance. This was successful as the pilot work identified problems that were both anticipated and not anticipated. From this a protocol was developed that would produce the required level of assessment.

The final study, utilising the protocol developed, established that there is a significant relationship between velocity and force. In addition further support to the asymmetrical nature of paddling technique at elite level kayaking has been identified, indicating a possible importance of asymmetry in performance. It has also been established that the activation of the external obliques and rectus abdominus provide significant contributions to the production of both force and velocity. The range of lumbar rotation also exhibited a significant role within technique, with lower ranges of motion resulting in higher boat velocities. The interaction of these findings identifies that it is important to have a stable lower trunk during paddling to ensure effective force development and resultantly higher boat velocity, indicating effective force transference. A further significant contribution was identified from the left rectus femoris enabling greater force and velocity production. Finally important roles were identified for the gastrocnemius, latissimus dorsi, knee extension and rotation of the thoracic spine during paddling.

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Appendix A

Notational Analysis Raw Data and Statistics

The following appendix contains the raw data and descriptive statistics from the notational analysis. The legend below defines the abbreviations used in the statistical package.

Legend:

Subnum – Subject Number

Level – Ability level

1 = International

2 = National

3 = Club

Distance – Event Distance

1 = 200m

2 = 500m

Competition – Type of Event

1 = K1

2 = K2

ltm – Lateral trunk motion

legmot – Leg Motion

legflex – Leg Flexion

legext – Leg Extension

forlean – Forward Lean

changeful – Change in Forward Lean

trunkrot – Trunk Rotation

pulaflex – Pull Arm Flexion

pussaext – Push Arm Extension

pusahi – Push Arm Height

headmot – Head Motion

boatmot – Boat Motion

strokew – Stroke Width

grip – grip

bladent – Blade Entry to Centre Line

p_to_v – Paddle to Vertical

kneeprox – Knee Proximity

bounce – Bouncing

rock – Rocking

arm_leg – Arm-leg Timing

foreach – Forward Reach

bareach – Backward Reach

spm – Stroke Rate

stime – Stroke Time

ptime – Pull Time

gtime – Glide Time

ptage – Pull time as a percentage of total stroke time

gtage – Glide time as a percentage of total stroke time

time – Race Time

	subnum	gender	level	distance	comp	ltm	legmot
1	1	female	internation	200	k1	2.0	3.0
2	2	female	internation	200	k1	1.0	2.0
3	3	female	internation	200	k1	1.0	2.0
4	4	female	internation	200	k1	1.0	4.0
5	5	female	internation	200	k1	1.0	4.0
6	6	female	internation	200	k1	1.0	3.0
7	7	female	internation	200	k1	1.0	4.0
8	8	female	internation	200	k1	1.0	4.0
9	9	female	internation	200	k1	1.0	3.0
10	10	male	internation	200	k1	1.0	3.0
11	11	male	internation	200	k1	1.0	3.0
12	12	male	internation	200	k1	1.0	3.0
13	13	male	internation	200	k1	1.0	3.0
14	14	male	internation	200	k1	1.0	3.0
15	15	male	internation	200	k1	1.0	3.0
16	16	male	internation	200	k1	2.0	3.0
17	17	male	internation	200	k1	1.0	3.0
18	18	male	internation	200	k1	1.0	3.0
19	19	male	internation	200	k1	2.0	3.0
20	20	male	internation	200	k1	1.0	3.0
21	21	male	internation	200	k1	2.0	2.0
22	22	male	internation	200	k1	1.0	4.0
23	23	male	internation	200	k1	2.0	4.0
24	24	male	internation	200	k1	1.0	3.0
25	25	male	internation	200	k1	1.0	4.0
26	26	male	internation	500	k1	1.0	4.0
27	27	male	internation	500	k1	2.0	3.0
28	28	male	internation	500	k1	1.0	3.0
29	29	male	internation	500	k1	1.0	4.0
30	30	male	internation	500	k1	1.0	4.0
31	31	male	internation	500	k1	2.0	3.0
32	32	male	internation	500	k1	2.0	3.0
33	33	male	internation	500	k1	1.0	3.0
34	34	female	internation	500	k1	1.0	3.0
35	35	female	internation	500	k1	2.0	2.0
36	36	female	internation	500	k1	1.0	2.0
37	37	female	internation	500	k1	1.0	4.0
38	38	female	internation	500	k1	.0	3.0
39	39	female	internation	500	k1	2.0	4.0
40	40	female	internation	500	k1	1.0	3.0
41	41	female	internation	500	k1	3.0	3.0
42	42	male	internation	500	k2	1.0	3.0
43	43	male	internation	500	k2	1.0	3.0

	legflex	legext	forlean	changefl	trunkrot	pulaflex	pusaext
1	3.0	3.0	3.0	1.0	3.0	2.0	2.0
2	2.0	3.0	2.0	3.0	2.0	4.0	2.0
3	2.0	1.0	3.0	.0	3.0	3.0	1.0
4	4.0	4.0	1.0	.0	2.0	2.0	2.0
5	3.0	4.0	4.0	2.0	3.0	5.0	3.0
6	3.0	3.0	1.0	1.0	2.0	2.0	2.0
7	4.0	3.0	2.0	.0	3.0	4.0	3.0
8	3.0	4.0	2.0	.0	3.0	3.0	2.0
9	3.0	3.0	2.0	.0	3.0	4.0	2.0
10	3.0	3.0	1.0	.0	1.0	3.0	2.0
11	3.0	3.0	1.0	.0	2.0	3.0	2.0
12	3.0	3.0	3.0	.0	3.0	2.0	3.0
13	3.0	3.0	1.0	.0	3.0	4.0	3.0
14	4.0	2.0	.0	.0	3.0	4.0	1.0
15	4.0	2.0	.0	.0	2.0	3.0	2.0
16	4.0	3.0	1.0	.0	2.0	4.0	2.0
17	3.0	4.0	1.0	.0	3.0	3.0	3.0
18	4.0	1.0	2.0	.0	2.0	3.0	3.0
19	3.0	1.0	2.0	.0	3.0	3.0	1.0
20	3.0	3.0	1.0	.0	3.0	4.0	2.0
21	2.0	4.0	2.0	.0	3.0	3.0	2.0
22	3.0	3.0	1.0	.0	3.0	3.0	2.0
23	4.0	4.0	1.0	.0	3.0	5.0	2.0
24	3.0	3.0	1.0	.0	2.0	4.0	3.0
25	3.0	4.0	.5	.0	3.0	4.0	2.0
26	4.0	4.0	.0	.0	3.0	4.0	2.0
27	3.0	3.0	1.0	.0	3.0	4.0	2.0
28	5.0	3.0	2.0	.0	1.0	3.0	3.0
29	3.0	5.0	1.0	.0	3.0	4.0	3.0
30	3.0	4.0	.0	.0	2.0	3.0	3.0
31	3.0	3.0	1.0	.0	3.0	4.0	3.0
32	4.0	2.0	.0	.0	2.0	3.0	3.0
33	3.0	3.0	1.0	.0	2.0	4.0	3.0
34	3.0	4.0	2.0	.0	3.0	3.0	2.0
35	2.0	4.0	3.0	1.0	3.0	4.0	2.0
36	2.0	3.0	1.0	.0	3.0	4.0	3.0
37	4.0	3.0	1.0	.0	2.0	3.0	3.0
38	4.0	3.0	1.0	.0	3.0	4.0	3.0
39	4.0	3.0	3.0	.5	3.0	3.0	2.0
40	4.0	3.0	2.0	.0	4.0	4.0	3.0
41	3.0	3.0	2.0	1.0	2.0	3.0	2.0
42	3.0	3.0	1.0	.0	4.0	3.0	3.0
43	3.0	3.0	2.0	.0	4.0	4.0	3.0

	pusahi	headmot	boatmot	strokew	grip	bladent	p_to_v
1	5.0	1.0	3.0	2.0	3.0	2.0	2.0
2	5.0	1.0	4.0	3.0	3.0	2.0	2.0
3	5.0	1.0	1.0	3.0	3.0	2.0	1.0
4	4.0	1.0	2.0	2.0	4.0	2.0	2.0
5	5.0	.0	1.0	3.0	3.0	2.0	4.0
6	4.0	1.0	2.0	2.0	3.0	2.0	3.0
7	4.5	1.0	2.0	2.0	4.0	2.0	2.0
8	4.0	1.0	1.0	3.0	2.0	2.0	2.0
9	5.0	.0	1.0	3.0	3.0	2.0	2.0
10	4.0	2.0	1.0	1.0	3.0	2.0	2.0
11	2.0	.0	1.0	1.0	4.0	2.0	2.0
12	.0	1.0	1.0	2.0	3.0	2.0	2.0
13	3.0	.0	1.0	3.0	3.0	2.0	3.0
14	3.0	.0	1.0	2.0	2.0	2.0	2.0
15	2.0	.0	2.0	2.0	2.0	2.0	2.0
16	3.0	1.0	1.0	2.0	4.0	2.0	2.0
17	3.0	1.0	2.0	2.0	1.0	2.0	2.0
18	3.0	.0	1.0	3.0	3.0	2.0	2.0
19	3.0	.0	1.0	2.0	3.0	2.0	4.0
20	3.0	1.0	1.0	2.0	3.0	1.0	4.0
21	4.0	1.0	2.0	2.0	4.0	2.0	2.0
22	3.0	1.0	1.0	2.0	3.0	2.0	1.0
23	4.0	1.0	3.0	2.0	3.0	2.0	2.0
24	4.0	1.0	2.0	2.0	1.0	2.0	3.0
25	4.0	1.0	2.0	3.0	3.0	2.0	4.0
26	3.0	1.0	1.0	3.0	2.0	2.0	2.0
27	4.0	.0	2.0	3.0	2.0	2.0	2.0
28	3.0	.0	1.0	3.0	2.0	2.0	2.0
29	3.0	1.0	3.0	4.0	2.0	1.0	1.0
30	4.0	.0	.5	3.0	3.0	1.0	2.5
31	3.0	1.0	.5	3.0	2.0	2.0	3.0
32	3.0	.0	1.0	4.0	3.0	1.0	1.5
33	3.0	1.0	1.0	3.0	2.0	2.0	3.0
34	5.0	1.0	1.0	4.0	2.0	2.0	3.0
35	3.0	2.0	.0	3.0	3.0	1.0	2.0
36	4.0	2.0	1.0	3.0	2.0	2.0	2.0
37	3.0	.0	1.0	3.0	2.0	2.0	3.0
38	4.0	.0	1.0	3.0	2.0	1.0	2.0
39	4.0	.0	1.0	4.0	3.0	3.0	3.0
40	4.0	.0	1.0	3.0	2.0	2.0	2.0
41	3.0	.0	2.0	4.0	2.0	1.0	1.0
42	3.0	1.0	1.0	3.0	2.0	1.0	1.0
43	2.0	1.0	1.0	2.0	2.0	1.0	1.0

	kneeprox	bounce	rock	arm_leg	foreach	bareach	spm
1	2.0	3.0	2.0	2.0	5.0	2.0	62.50
2	2.0	4.0	1.0	3.0	4.0	2.0	60.00
3	2.0	1.0	1.0	1.0	2.0	1.0	75.00
4	2.0	.0	2.0	2.0	3.0	1.0	68.18
5	2.0	1.0	1.0	2.0	5.0	1.0	62.50
6	2.0	2.0	1.0	2.0	3.0	2.0	68.18
7	2.0	2.0	1.0	2.0	2.0	2.0	62.50
8	2.0	1.0	1.0	2.0	3.0	1.0	60.00
9	2.0	1.0	1.0	2.0	4.0	1.0	57.69
10	2.0	.0	1.0	2.0	2.0	2.0	71.43
11	2.0	.0	1.0	1.0	2.0	2.0	75.00
12	2.0	1.0	1.0	1.0	4.0	1.0	71.43
13	3.0	1.0	1.0	2.0	3.0	3.0	65.23
14	1.0	1.0	1.0	2.0	2.0	2.0	71.43
15	1.0	2.0	1.0	2.0	3.0	2.0	65.22
16	1.0	1.0	1.0	1.0	4.0	2.0	65.22
17	2.0	1.0	2.0	2.0	3.0	1.0	65.22
18	2.0	1.0	1.0	2.0	3.0	1.0	68.18
19	2.0	1.0	1.0	2.0	3.0	2.0	65.22
20	3.0	1.0	1.0	2.0	3.0	3.0	75.00
21	2.0	2.0	2.0	1.0	3.0	3.0	68.18
22	2.0	1.0	1.0	2.0	4.0	2.0	68.18
23	2.0	2.0	3.0	1.0	3.0	3.0	68.18
24	2.0	2.0	2.0	2.0	4.0	2.0	71.43
25	2.0	2.0	2.0	1.0	3.0	2.0	68.18
26	2.0	1.0	1.0	1.0	2.0	3.0	60.00
27	2.0	.5	2.0	1.0	3.0	2.0	62.50
28	1.0	1.0	1.0	2.0	3.0	1.0	51.72
29	2.0	.0	3.0	1.0	2.0	3.0	65.22
30	2.0	.0	1.0	1.0	3.0	3.0	62.50
31	3.0	.0	1.0	2.0	3.0	3.0	60.00
32	2.0	1.0	2.0	2.0	3.0	3.0	60.00
33	3.0	1.0	1.0	2.0	2.0	2.0	60.00
34	2.0	1.0	1.0	2.0	4.0	2.0	51.72
35	2.0	.0	.0	2.0	2.0	3.0	60.00
36	2.0	1.0	1.0	2.0	2.0	4.0	57.69
37	2.0	1.0	1.0	2.0	3.0	2.0	53.57
38	2.0	.0	1.0	2.0	3.0	2.0	60.00
39	2.0	.0	1.0	1.0	3.0	3.0	53.57
40	2.0	1.0	1.0	2.0	3.0	3.0	57.69
41	2.0	1.0	2.0	2.0	2.0	4.0	48.39
42	2.0	1.0	1.0	2.0	4.0	2.0	62.50
43	2.0	1.0	1.0	2.0	3.0	2.0	62.50

	stime	ptime	gtime	ptage	gtage	time
1	.96	.48	.48	50.00	50.00	45.381
2	1.00	.40	.60	40.00	60.00	45.381
3	.80	.40	.40	50.00	50.00	45.381
4	.88	.44	.44	50.00	50.00	45.450
5	.96	.52	.44	54.17	45.83	42.674
6	.88	.48	.40	54.54	45.46	42.674
7	.96	.48	.48	50.00	50.00	42.674
8	1.00	.44	.56	44.00	56.00	45.099
9	1.04	.56	.48	53.85	46.15	45.317
10	.84	.40	.44	47.62	52.38	38.523
11	.80	.48	.32	60.00	40.00	38.523
12	.84	.48	.36	57.14	42.86	38.523
13	.92	.48	.44	52.17	47.83	39.114
14	.84	.40	.44	53.85	46.15	39.581
15	.92	.52	.40	56.52	43.48	39.581
16	.92	.56	.36	60.87	39.13	39.581
17	.92	.52	.40	56.52	43.48	40.027
18	.88	.52	.36	59.09	40.91	38.073
19	.92	.52	.40	56.52	43.48	38.316
20	.80	.48	.32	60.00	40.00	38.441
21	.88	.56	.32	63.64	36.36	38.441
22	.88	.44	.44	50.00	50.00	39.112
23	.88	.48	.40	54.54	45.46	39.112
24	.84	.44	.40	52.38	47.62	39.112
25	.88	.40	.48	45.45	54.56	39.112
26	1.00	.52	.48	52.00	48.00	98.901
27	.96	.64	.32	66.67	33.33	99.807
28	1.16	.72	.44	62.01	37.99	106.020
29	.92	.56	.36	60.87	39.13	103.877
30	.96	.52	.44	54.17	45.83	109.534
31	1.00	.64	.36	64.00	36.00	102.200
32	1.00	.52	.48	52.00	48.00	101.937
33	1.00	.56	.44	56.00	44.00	102.000
34	1.16	.60	.56	51.72	48.28	112.639
35	1.00	.60	.40	60.00	40.00	116.469
36	1.04	.54	.50	51.92	48.08	119.295
37	1.12	.64	.48	57.14	42.86	119.505
38	1.00	.50	.50	50.00	50.00	115.426
39	1.12	.64	.48	57.14	42.86	112.416
40	1.04	.60	.44	57.69	42.31	113.316
41	1.24	.68	.56	54.84	45.16	127.032
42	.96	.56	.40	58.33	41.67	96.001
43	.96	.56	.40	58.33	41.67	96.001

	subnum	gender	level	distance	comp	ltm	legmot
44	44	male	internation	500	k2	1.0	3.0
45	45	male	internation	500	k2	1.0	3.0
46	46	male	internation	500	k2	1.0	3.0
47	47	male	internation	500	k2	1.0	3.0
48	48	male	internation	500	k2	1.0	3.0
49	49	male	internation	500	k2	1.0	3.0
50	50	male	internation	500	k2	1.0	3.0
51	51	male	internation	500	k2	2.0	3.0
52	52	male	internation	500	k2	1.0	3.0
53	53	male	internation	500	k2	1.0	3.0
54	54	female	internation	500	k2	1.0	3.0
55	55	female	internation	500	k2	1.0	3.0
56	56	female	internation	500	k2	1.0	4.0
57	57	female	internation	500	k2	1.0	4.0
58	58	female	internation	500	k2	2.0	3.0
59	59	female	internation	500	k2	2.0	3.0
60	60	female	internation	500	k2	1.0	3.0
61	61	female	internation	500	k2	1.0	3.0
62	62	female	internation	500	k2	1.0	3.0
63	63	female	internation	500	k2	1.0	3.0
64	64	male	internation	500	k1	1.0	3.0
65	65	male	internation	500	k1	2.0	3.0
66	66	male	internation	500	k1	2.0	3.0
67	67	male	internation	500	k1	1.0	4.0
68	68	female	internation	500	k1	1.0	4.0
69	69	female	internation	500	k1	1.0	3.0
70	70	female	internation	500	k1	2.0	4.0
71	71	female	internation	500	k1	1.0	3.0
72	72	female	internation	500	k1	1.0	3.0
73	73	male	internation	500	k2	1.0	3.0
74	74	male	internation	500	k2	1.0	3.0
75	75	male	internation	500	k2	.0	3.0
76	76	male	internation	500	k2	1.0	3.0
77	77	male	internation	500	k2	1.0	3.0
78	78	male	internation	500	k2	1.0	3.0
79	79	male	national	200	k1	1.5	3.0
80	80	male	national	200	k1	1.5	3.5
81	81	male	national	200	k1	1.5	3.5
82	82	male	national	200	k1	1.0	1.0
83	83	male	national	200	k1	1.0	1.0
84	84	female	national	200	k1	2.0	3.0
85	85	female	national	200	k1	1.5	3.5
86	86	female	club	200	k1	1.0	.0

	legflex	legext	forlean	changefl	trunkrot	pulaflex	pusaext
44	3.0	3.0	1.0	.0	3.0	4.0	3.0
45	4.0	3.0	.0	.0	3.0	4.0	3.0
46	4.0	3.0	1.0	.0	3.0	2.0	2.0
47	3.0	4.0	1.0	.0	3.0	2.0	2.0
48	3.0	4.0	.0	.0	3.0	4.0	3.0
49	3.0	3.0	2.0	.0	4.0	3.0	3.0
50	4.0	3.0	1.0	.0	3.0	3.0	3.0
51	3.0	4.0	.5	.0	2.0	3.0	2.0
52	4.0	3.0	.0	.0	3.0	4.0	2.0
53	2.0	4.0	1.0	.0	4.0	4.0	3.0
54	3.0	3.0	.0	.0	4.0	4.0	3.0
55	3.0	3.0	1.0	.0	3.0	4.0	3.0
56	4.0	4.0	2.0	.0	2.0	3.0	2.0
57	4.0	4.0	3.0	1.0	3.0	3.0	3.0
58	3.0	4.0	2.0	.0	2.0	4.0	3.0
59	3.0	4.0	2.0	1.0	2.0	4.0	2.0
60	3.0	4.0	1.0	.0	3.0	3.0	2.0
61	3.0	4.0	1.0	.0	3.0	4.0	2.0
62	3.0	3.0	1.0	.0	2.0	4.0	2.0
63	3.0	3.0	1.0	.0	3.0	4.0	2.0
64	4.0	2.0	.0	.0	3.0	5.0	3.0
65	3.0	4.0	1.0	.0	4.0	4.0	3.0
66	3.0	4.0	1.0	.0	4.0	4.0	3.0
67	4.0	4.0	1.0	.0	3.0	4.0	3.0
68	3.0	4.0	1.0	.0	3.0	4.0	2.0
69	3.0	2.0	2.0	.0	2.0	3.0	2.0
70	3.0	4.0	1.0	1.0	2.0	4.0	2.0
71	2.0	4.0	2.0	.0	3.0	3.0	3.0
72	3.0	3.0	1.0	.0	4.0	3.0	3.0
73	2.0	4.0	.0	.0	3.0	4.0	3.0
74	2.0	4.0	1.0	.0	3.0	4.0	3.0
75	3.0	4.0	1.0	.0	3.0	4.0	3.0
76	3.0	4.0	1.0	.0	3.0	4.0	3.0
77	3.0	3.0	2.0	.0	2.0	3.0	3.0
78	3.0	3.0	1.0	.0	3.0	3.0	3.0
79	3.0	3.0	1.5	.0	2.0	2.0	2.0
80	4.0	2.5	2.5	.0	3.0	3.5	1.5
81	4.0	2.5	.0	.0	1.0	3.5	1.5
82	.0	.0	1.0	.0	1.0	3.5	2.5
83	1.0	1.0	1.0	.5	2.0	3.5	3.0
84	2.5	2.5	2.0	.0	3.5	3.5	2.5
85	3.5	3.0	2.5	1.5	2.5	2.5	2.0
86	.0	.0	2.0	1.0	2.0	3.0	2.5

	pusahi	headmot	boatmot	strokew	grip	bladent	p_to_v
44	3.0	1.0	2.0	3.0	2.0	2.0	2.0
45	4.0	2.0	2.0	3.0	1.0	2.0	2.0
46	3.0	1.0	1.0	3.0	3.0	2.0	2.0
47	2.0	.0	1.0	3.0	3.0	2.0	2.0
48	3.0	.0	1.0	3.0	2.0	1.0	1.0
49	4.0	2.0	1.0	4.0	2.0	2.0	2.0
50	4.0	1.0	1.0	3.0	2.0	2.0	2.0
51	4.0	1.0	1.0	3.0	1.0	2.0	2.0
52	3.0	1.0	1.0	4.0	4.0	1.0	1.0
53	3.0	.0	1.0	3.0	2.0	2.0	2.0
54	3.0	1.0	1.0	3.0	2.0	1.0	1.0
55	3.0	1.0	1.0	3.0	2.0	2.0	2.0
56	3.0	1.0	2.0	3.0	3.0	2.0	3.0
57	4.0	1.0	2.0	3.0	2.0	2.0	3.0
58	3.0	.0	1.0	3.0	3.0	2.0	2.0
59	3.0	.0	1.0	4.0	2.0	2.0	2.0
60	2.0	.0	1.0	3.0	2.0	1.0	2.0
61	3.0	.0	1.0	3.0	2.0	1.0	2.0
62	4.0	.0	1.0	3.0	1.0	1.0	2.0
63	4.0	1.0	1.0	3.0	1.0	1.0	2.0
64	3.0	1.0	1.0	4.0	2.0	1.0	2.0
65	4.0	.0	2.0	4.0	3.0	2.0	2.0
66	4.0	2.0	1.0	4.0	3.0	1.0	2.0
67	3.0	1.0	1.0	3.0	2.0	1.0	1.0
68	4.0	1.0	1.0	4.0	2.0	2.0	2.0
69	4.0	1.0	3.0	3.0	2.0	1.0	1.0
70	2.0	.0	1.0	4.0	1.0	1.0	1.0
71	4.0	1.0	1.0	3.0	3.0	2.0	2.0
72	2.0	1.0	1.0	3.0	2.0	1.0	1.0
73	4.0	1.0	1.0	4.0	2.0	2.0	2.0
74	3.0	1.0	1.0	3.0	3.0	3.0	3.0
75	4.0	1.0	1.0	3.0	1.0	1.0	1.0
76	4.0	1.0	1.0	3.0	2.0	2.0	2.0
77	4.0	1.0	1.0	3.0	3.0	1.0	1.0
78	4.0	.0	1.0	3.0	2.0	1.0	1.0
79	4.0	2.5	1.0	1.0	2.5	2.0	4.0
80	3.0	.5	2.5	2.5	1.5	2.0	2.0
81	3.0	.0	1.0	1.5	3.5	1.5	2.0
82	2.0	.0	4.0	1.0	1.0	3.0	4.5
83	3.0	.0	3.0	3.5	4.0	1.5	2.5
84	4.0	1.0	1.5	2.0	1.5	1.5	2.0
85	3.0	2.0	1.5	2.5	2.0	2.0	2.5
86	5.0	2.0	3.5	3.0	2.5	2.0	3.5

	kneeprox	bounce	rock	arm_leg	foreach	bareach	spm
44	2.0	1.0	2.0	2.0	3.0	3.0	62.50
45	2.0	1.0	2.0	2.0	3.0	2.0	62.50
46	2.0	1.0	1.0	2.0	2.0	3.0	65.22
47	2.0	1.0	1.0	2.0	4.0	3.0	65.22
48	2.0	1.0	1.0	1.0	3.0	2.0	62.50
49	2.0	1.0	1.0	2.0	2.0	3.0	62.50
50	2.0	1.0	1.0	1.0	2.0	2.0	57.69
51	2.0	1.0	1.0	2.0	2.0	2.0	57.69
52	2.0	1.0	1.0	2.0	4.0	3.0	60.00
53	2.0	1.0	1.0	1.0	3.0	1.0	60.00
54	2.0	1.0	1.0	2.0	3.0	2.0	53.57
55	2.0	1.0	1.0	2.0	2.0	3.0	53.57
56	1.0	1.0	2.0	1.0	3.0	2.0	62.50
57	1.0	1.0	2.0	1.0	3.0	3.0	62.50
58	2.0	1.0	1.0	1.0	3.0	2.0	62.50
59	2.0	1.0	1.0	1.0	3.0	2.0	62.50
60	2.0	1.0	.0	1.0	3.0	2.0	62.50
61	2.0	1.0	.0	1.0	3.0	3.0	62.50
62	2.0	1.0	1.0	2.0	3.0	2.0	57.69
63	2.0	1.0	1.0	2.0	3.0	2.0	57.69
64	2.0	.0	1.0	1.0	4.0	3.0	55.55
65	2.0	1.0	2.0	2.0	3.0	2.0	57.69
66	2.0	.0	1.0	1.0	3.0	3.0	62.50
67	2.0	1.0	1.0	2.0	3.0	3.0	65.22
68	2.0	1.0	1.0	1.0	3.0	2.0	55.56
69	2.0	2.0	3.0	1.0	3.0	2.0	57.69
70	2.0	1.0	1.0	2.0	2.0	3.0	53.57
71	2.0	1.0	1.0	1.0	4.0	2.0	60.00
72	2.0	1.0	1.0	1.0	3.0	2.0	53.57
73	2.0	1.0	1.0	2.0	3.0	3.0	60.00
74	2.0	1.0	1.0	2.0	2.0	4.0	60.00
75	2.0	1.0	1.0	1.0	3.0	3.0	60.00
76	2.0	1.0	1.0	2.0	3.0	3.0	60.00
77	2.0	1.0	1.0	2.0	3.0	2.0	55.56
78	2.0	1.0	1.0	2.0	3.0	2.0	55.56
79	2.5	1.0	1.0	3.0	3.0	1.0	57.69
80	2.0	2.0	1.5	2.5	4.0	1.0	55.55
81	3.0	1.0	1.0	2.5	2.0	2.0	68.18
82	.0	3.0	3.5	.0	2.0	1.0	62.50
83	2.0	3.0	2.5	2.0	3.0	2.0	57.69
84	1.5	1.0	1.0	1.0	3.0	2.0	55.55
85	2.0	1.5	1.0	3.5	2.0	2.0	60.00
86	.0	3.0	3.5	.0	3.0	3.0	62.50

	stime	ptime	gtime	ptage	gtage	time
44	.96	.60	.36	62.50	37.50	96.334
45	.96	.60	.36	62.50	37.50	96.334
46	.92	.48	.44	52.17	47.83	96.941
47	.92	.48	.44	52.17	47.83	96.941
48	.96	.48	.48	50.00	50.00	94.038
49	.96	.48	.48	50.00	50.00	94.038
50	1.04	.64	.40	61.54	38.46	96.444
51	1.04	.64	.40	61.54	38.46	96.444
52	1.00	.52	.48	52.00	48.00	94.454
53	1.00	.52	.48	52.00	48.00	94.454
54	1.12	.60	.52	53.57	46.43	104.357
55	1.12	.60	.52	53.57	46.43	104.357
56	.96	.54	.42	56.25	43.75	105.653
57	.96	.56	.40	58.33	41.67	105.653
58	.96	.52	.44	54.17	45.83	107.150
59	.96	.52	.44	54.17	45.83	107.150
60	.96	.50	.46	52.08	47.92	103.690
61	.96	.52	.44	52.08	47.92	103.690
62	1.04	.56	.48	53.85	46.15	106.520
63	1.04	.56	.48	53.85	46.15	106.520
64	1.08	.64	.44	59.26	40.74	103.870
65	1.04	.54	.50	51.92	48.08	106.137
66	.96	.60	.36	62.50	37.50	101.264
67	.92	.48	.44	52.17	47.83	106.710
68	1.08	.60	.48	55.56	44.44	119.919
69	1.04	.52	.52	50.00	50.00	120.798
70	1.12	.56	.56	50.00	50.00	114.289
71	1.00	.52	.48	52.00	48.00	115.412
72	1.12	.60	.52	53.57	46.43	116.032
73	1.00	.56	.44	56.00	44.00	95.421
74	1.00	.56	.44	56.00	44.00	95.421
75	1.00	.50	.50	50.00	50.00	97.861
76	1.00	.56	.44	56.00	44.00	97.861
77	1.08	.52	.56	48.15	52.85	92.945
78	1.08	.54	.54	50.00	50.00	92.945
79	1.04	.56	.48	53.85	46.15	39.840
80	1.08	.60	.48	55.56	44.44	41.900
81	.88	.40	.48	45.45	54.55	44.440
82	.96	.36	.60	37.50	62.50	47.100
83	1.04	.44	.60	42.31	57.69	48.510
84	1.08	.56	.52	51.85	48.15	43.020
85	1.00	.56	.44	56.00	44.00	49.390
86	.96	.48	.48	50.00	50.00	49.880

	subnum	gender	level	distance	comp	ltm	legmot
87	87	female	club	200	k1	1.0	2.5
88	88	male	national	500	k1	.0	2.0
89	89	male	national	500	k1	1.0	4.0
90	90	male	national	500	k1	2.0	4.0
91	91	male	national	500	k1	1.0	3.0
92	92	male	national	500	k1	2.0	3.0
93	93	male	national	500	k1	1.0	4.0
94	94	male	national	500	k1	1.0	3.0
95	95	male	national	500	k1	1.0	3.0
96	96	female	national	500	k1	1.0	4.0
97	97	female	national	500	k1	1.0	3.0
98	98	male	national	500	k1	1.0	3.0
99	99	male	national	500	k1	1.0	3.0
100	100	male	national	500	k1	1.0	3.0
101	101	male	national	500	k1	2.0	3.0
102	102	male	national	500	k1	1.0	3.0
103	103	female	club	500	k1	2.0	3.0
104	104	female	club	500	k1	.0	2.0
105	105	female	club	500	k1	3.0	1.0
106	106	female	club	500	k1	2.0	4.0
107	107	female	club	500	k1	2.0	3.0
108	108	male	club	500	k1	.0	3.0
109	109	male	club	500	k1	1.0	2.0
110	110	male	club	500	k1	1.0	2.0
111	111	male	club	500	k1	1.0	2.0
112	112	male	club	500	k1	1.0	2.0
113	113	male	national	200	k1	1.0	3.0
114	114	male	national	200	k1	2.0	3.0
115	115	female	club	200	k1	1.0	4.0
116	116	female	national	200	k1	1.0	3.0
117	117	female	national	200	k1	2.0	2.0
118	118	male	national	500	k1	1.0	2.0
119	119	male	national	500	k1	1.0	3.0
120	120	male	national	500	k1	1.0	3.0
121	121	male	national	500	k1	1.0	3.0
122	122	male	national	500	k1	1.0	3.0
123	123	male	national	500	k1	1.0	2.0
124	124	male	national	500	k1	.0	2.0
125	125	male	national	500	k1	1.0	3.0
126	126	female	national	500	k1	1.0	3.0
127	127	female	national	500	k1	1.0	3.0
128	128	female	national	500	k1	.0	3.0
129	129	male	national	500	k1	1.0	3.0

	legflex	legext	forlean	changefl	trunkrot	pulaflex	pusaext
87	2.0	2.5	1.0	1.0	1.0	4.0	3.0
88	2.0	2.0	.0	.0	2.0	4.0	4.0
89	4.0	4.0	1.0	.0	2.0	4.0	2.0
90	4.0	3.0	1.0	.0	3.0	4.0	3.0
91	3.0	3.0	1.0	.0	2.0	4.0	3.0
92	3.0	3.0	2.0	.0	3.0	3.0	3.0
93	4.0	3.0	1.0	.0	2.0	4.0	3.0
94	3.0	3.0	1.0	.0	2.0	4.0	3.0
95	3.0	3.0	1.0	.0	2.0	4.0	3.0
96	4.0	3.0	1.0	.0	4.0	4.0	4.0
97	3.0	3.0	3.0	.0	3.0	4.0	3.0
98	3.0	3.0	1.0	.0	3.0	4.0	3.0
99	2.0	4.0	1.0	.0	3.0	4.0	3.0
100	3.0	4.0	.0	.0	3.0	4.0	3.0
101	3.0	3.0	.0	.0	3.0	4.0	3.0
102	2.0	4.0	2.0	.0	3.0	2.0	2.0
103	3.0	3.0	2.0	.0	2.0	4.0	3.0
104	2.0	3.0	2.0	.0	1.0	2.0	2.0
105	1.0	1.0	2.0	4.0	.5	4.0	4.0
106	4.0	4.0	2.0	1.0	4.0	3.0	1.0
107	3.0	3.0	1.0	.0	2.0	1.0	1.0
108	3.0	3.0	1.0	1.0	2.0	4.0	4.0
109	2.0	2.0	1.0	1.0	1.0	2.0	3.0
110	2.0	2.0	1.0	.0	1.0	3.0	3.0
111	2.0	2.0	1.0	1.0	2.0	4.0	3.0
112	1.0	3.0	3.0	2.0	1.0	2.0	2.0
113	2.0	4.0	1.0	.0	2.0	3.0	2.0
114	3.0	3.0	2.0	.0	3.0	2.0	4.0
115	4.0	4.0	3.0	.0	2.0	2.0	3.0
116	3.0	3.0	3.0	1.0	2.0	3.0	2.0
117	2.0	2.0	3.0	.0	3.0	2.0	2.0
118	3.0	2.0	1.0	1.0	3.0	4.0	1.0
119	3.0	3.0	3.0	.0	2.0	2.0	2.0
120	3.0	3.0	2.0	.0	2.0	4.0	3.0
121	3.0	3.0	.0	.0	3.0	4.0	4.0
122	3.0	3.0	1.0	.0	1.0	3.0	3.0
123	2.0	2.0	1.0	.0	3.0	4.0	2.0
124	2.0	2.0	.0	.0	2.0	3.0	2.0
125	4.0	3.0	1.0	.0	2.0	5.0	3.0
126	3.0	3.0	2.0	1.0	2.0	3.0	3.0
127	3.0	3.0	2.0	.0	2.0	4.0	3.0
128	4.0	2.0	3.0	1.0	2.0	5.0	4.0
129	4.0	2.0	1.0	.0	2.0	3.0	3.0

	pusahi	headmot	boatmot	strokew	grip	bladent	p_to_v
87	4.0	.0	1.0	3.0	3.0	1.5	3.0
88	2.0	2.0	3.0	2.0	2.0	2.0	3.0
89	3.0	.0	1.0	2.0	3.0	2.0	2.0
90	3.0	1.0	2.0	3.0	4.0	2.0	2.0
91	4.0	2.0	1.0	3.0	2.0	2.0	2.0
92	3.0	2.0	2.0	3.0	2.0	2.0	2.0
93	3.0	1.0	2.0	3.0	3.0	2.0	2.0
94	4.0	.0	2.0	2.0	2.0	3.0	3.0
95	4.0	1.0	2.0	3.0	2.0	2.0	2.0
96	4.0	1.0	1.0	3.0	4.0	2.0	2.0
97	4.0	.0	2.0	3.0	3.0	1.0	2.0
98	4.0	.0	2.0	3.0	2.0	1.0	2.0
99	4.0	.0	1.0	3.0	2.0	2.0	3.0
100	4.0	.0	1.0	3.0	3.0	1.0	1.0
101	2.0	1.0	2.0	3.0	4.0	2.0	3.0
102	3.0	1.0	1.0	3.0	4.0	1.0	2.0
103	4.0	.0	1.0	2.0	3.0	2.0	2.0
104	2.0	.0	.5	2.0	2.0	2.0	4.0
105	2.0	2.0	4.0	1.0	1.0	3.0	4.0
106	3.0	3.0	4.0	2.0	2.0	3.0	3.0
107	1.0	3.0	3.0	2.0	2.0	2.0	4.0
108	3.0	1.0	3.0	2.0	2.0	2.0	3.0
109	4.0	1.0	4.0	3.0	3.0	2.0	3.0
110	1.0	.0	4.0	2.0	1.0	2.0	3.0
111	2.0	2.0	4.0	3.0	4.0	2.0	2.0
112	.5	2.0	3.0	1.0	3.0	3.0	4.0
113	2.0	.0	1.0	2.0	4.0	2.0	2.0
114	3.0	2.0	3.0	1.0	2.0	2.0	2.0
115	4.0	1.0	3.0	2.0	2.0	2.0	3.0
116	4.0	1.0	2.0	2.0	2.0	2.0	2.0
117	4.0	1.0	2.0	2.0	2.0	2.0	1.0
118	3.0	1.0	2.0	2.0	1.0	2.0	3.0
119	4.0	1.0	4.0	2.0	4.0	2.0	2.0
120	3.0	.0	1.0	3.0	2.0	2.0	2.0
121	4.0	.0	1.0	3.0	2.0	1.0	2.0
122	4.0	.0	2.0	3.0	3.0	2.0	3.0
123	4.0	1.0	1.0	3.0	2.0	2.0	2.0
124	3.0	.0	.0	2.0	2.0	2.0	2.0
125	4.0	.0	1.0	3.0	3.0	2.0	2.0
126	2.0	1.0	1.0	3.0	4.0	2.0	2.0
127	4.0	1.0	1.0	3.0	3.0	2.0	3.0
128	4.0	1.0	2.0	2.0	3.0	2.0	3.0
129	3.0	1.0	2.0	3.0	4.0	1.0	2.0

	kneeprox	bounce	rock	arm_leg	foreach	bareach	spm
87	2.0	1.0	.5	2.0	4.0	2.0	55.55
88	2.0	3.0	3.0	2.0	3.0	2.0	62.50
89	2.0	1.0	1.0	2.0	3.0	3.0	57.69
90	2.0	.0	3.0	1.0	3.0	3.0	60.00
91	3.0	1.0	1.0	3.0	3.0	2.0	55.56
92	2.0	2.0	1.0	3.0	2.0	4.0	53.57
93	3.0	2.0	1.0	2.0	3.0	4.0	62.50
94	2.0	2.0	1.0	2.0	3.0	3.0	51.72
95	3.0	2.0	2.0	2.0	1.0	3.0	55.56
96	2.0	1.0	1.0	2.0	3.0	4.0	53.57
97	3.0	1.0	2.0	2.0	2.0	3.0	62.50
98	2.0	1.0	2.0	2.0	3.0	3.0	60.00
99	2.0	1.0	1.0	1.0	3.0	1.0	62.50
100	3.0	1.0	1.0	1.0	1.0	3.0	60.00
101	3.0	2.0	2.0	2.0	2.0	3.0	56.60
102	2.0	1.0	.5	3.0	2.0	3.0	53.57
103	2.0	.5	1.0	2.0	2.0	3.0	51.72
104	3.0	.0	.5	2.0	3.0	3.0	53.57
105	3.0	4.0	4.0	4.0	1.0	3.0	48.39
106	3.0	1.0	4.0	3.0	1.0	2.0	45.45
107	4.0	3.0	3.0	3.0	1.0	2.0	46.87
108	3.0	3.0	3.0	3.0	3.0	3.0	53.57
109	3.0	4.0	3.0	3.0	2.0	4.0	48.39
110	3.0	3.0	4.0	3.0	2.0	2.0	57.69
111	3.0	4.0	3.0	3.0	1.0	3.0	45.45
112	3.0	1.0	4.0	4.0	2.0	3.0	44.12
113	2.0	.0	1.0	1.0	3.0	2.0	65.22
114	3.0	3.0	2.0	2.0	2.0	3.0	57.69
115	2.0	1.0	3.0	3.0	3.0	3.0	53.57
116	3.0	2.0	2.0	2.0	3.0	2.0	62.50
117	3.0	2.0	2.0	3.0	4.0	3.0	57.69
118	2.0	2.0	2.0	2.0	2.0	2.0	51.72
119	2.0	4.0	3.0	2.0	2.0	1.0	51.72
120	3.0	1.0	2.0	2.0	2.0	3.0	55.56
121	2.0	1.0	1.0	2.0	3.0	2.0	55.56
122	3.0	2.0	2.0	2.0	3.0	3.0	53.57
123	2.0	1.0	1.0	2.0	1.0	2.0	55.56
124	3.0	.0	.0	2.0	3.0	3.0	55.56
125	2.0	1.0	1.0	3.0	4.0	4.0	51.72
126	3.0	1.0	1.0	2.0	2.0	3.0	57.69
127	3.0	1.0	1.0	2.0	3.0	2.0	57.69
128	3.0	2.0	1.0	2.0	2.0	3.0	57.69
129	2.0	1.0	2.0	2.0	3.0	4.0	55.56

	stime	ptime	gtime	ptage	gtage	time
87	1.08	.52	.56	48.15	51.85	55.660
88	.96	.52	.44	54.17	45.83	106.510
89	1.04	.68	.36	65.38	34.62	107.180
90	1.00	.56	.44	56.00	44.00	104.960
91	1.08	.60	.48	55.56	44.44	104.890
92	1.12	.64	.48	57.14	42.86	118.640
93	.96	.58	.38	60.42	39.58	111.210
94	1.16	.68	.48	58.62	41.38	126.590
95	1.08	.64	.44	59.26	40.74	114.490
96	1.12	.64	.48	57.14	42.86	119.340
97	.96	.48	.48	50.00	50.00	117.040
98	1.00	.56	.44	56.00	44.00	104.830
99	.96	.52	.44	54.17	45.83	107.000
100	1.00	.52	.48	52.00	48.00	111.900
101	1.06	.64	.42	59.26	40.74	120.740
102	1.12	.70	.52	62.50	37.50	124.680
103	1.16	.56	.60	48.28	51.72	134.740
104	1.12	.64	.48	57.14	42.86	146.520
105	1.24	.68	.56	54.84	45.16	144.570
106	1.32	.60	.72	45.45	54.55	145.170
107	1.28	.56	.72	43.75	56.25	147.420
108	1.12	.56	.56	50.00	50.00	122.820
109	1.24	.64	.60	51.61	48.39	135.450
110	1.04	.56	.48	53.85	46.15	133.050
111	1.32	.68	.64	51.52	48.48	133.530
112	1.36	.84	.52	61.76	38.24	146.710
113	.92	.56	.36	60.87	39.13	42.750
114	1.04	.52	.52	50.00	50.00	41.390
115	1.12	.60	.52	53.57	46.43	49.560
116	.96	.52	.44	54.17	45.83	48.800
117	1.04	.56	.48	53.85	46.15	51.450
118	1.16	.72	.44	62.07	37.93	109.800
119	1.16	.60	.56	51.72	48.28	129.240
120	1.08	.56	.52	51.85	48.15	107.910
121	1.08	.64	.44	59.26	40.74	103.390
122	1.12	.64	.48	57.14	42.86	121.910
123	1.08	.60	.48	55.56	44.44	117.040
124	1.08	.60	.44	59.26	40.74	119.510
125	1.16	.72	.44	62.07	37.93	115.470
126	1.04	.56	.48	53.85	46.15	131.870
127	1.04	.56	.48	53.85	46.15	118.380
128	1.04	.60	.44	57.69	42.31	122.400
129	1.08	.60	.48	55.56	44.44	114.050

	subnum	gender	level	distance	comp	ltm	legmot
130	130	female	club	500	k1	2.0	2.0
131	131	female	club	500	k1	.0	2.0
132	132	male	club	500	k1	2.0	2.0
133	133	male	club	500	k1	2.0	2.0
134	134	male	club	500	k1	1.0	2.0
135	135	male	club	500	k1	1.0	2.0

	legflex	legext	forlean	changefl	trunkrot	pulaflex	pusaext
130	2.0	2.0	2.0	1.0	2.0	3.0	3.0
131	2.0	2.0	1.0	.0	2.0	3.0	1.0
132	2.0	2.0	1.0	.0	2.0	3.0	3.0
133	2.0	2.0	3.0	2.0	2.0	3.0	3.0
134	2.0	2.0	1.0	.0	2.0	3.0	3.0
135	2.0	2.0	2.0	.0	2.0	4.0	2.0

	pusahi	headmot	boatmot	strokew	grip	bladent	p_to_v
130	3.0	1.0	2.0	2.0	2.0	2.0	4.0
131	1.0	.0	1.0	2.0	2.0	2.0	4.0
132	3.0	1.0	2.0	2.0	2.0	2.0	2.0
133	1.0	1.0	4.0	2.0	2.0	3.0	4.0
134	3.0	1.0	2.0	2.0	3.0	2.0	2.0
135	2.0	.0	2.0	1.0	2.0	3.0	3.0

	kneeprox	bounce	rock	arm_leg	foreach	bareach	spm
130	3.0	2.0	2.0	3.0	2.0	3.0	60.00
131	3.0	1.0	1.0	4.0	2.0	2.0	50.00
132	2.0	3.0	1.0	2.0	3.0	1.0	55.56
133	3.0	4.0	4.0	3.0	2.0	2.0	53.57
134	3.0	2.0	3.0	3.0	3.0	3.0	46.88
135	3.0	1.0	3.0	3.0	2.0	2.0	46.88

	stime	ptime	gtime	ptage	gtage	time
130	1.00	.56	.44	56.00	44.00	148.790
131	1.20	.54	.66	45.00	55.00	147.540
132	1.08	.52	.56	48.15	51.85	121.390
133	1.12	.64	.48	57.14	42.86	141.920
134	1.28	.64	.64	50.00	50.00	133.050
135	1.28	.64	.64	50.00	50.00	141.460

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
ltm	international	78	1.205	.4930	.0558	1.094	1.316	.0	3.0
	national	38	1.132	.5025	.0815	.966	1.297	.0	2.0
	club	19	1.263	.8057	.1848	.875	1.651	.0	3.0
	Total	135	1.193	.5463	.0470	1.100	1.286	.0	3.0
legmot	international	78	3.154	.5116	.0579	3.038	3.269	2.0	4.0
	national	38	2.908	.6863	.1113	2.682	3.133	1.0	4.0
	club	19	2.237	.9185	.2107	1.794	2.680	.0	4.0
	Total	135	2.956	.7004	.0603	2.836	3.075	.0	4.0
legflex	international	78	3.179	.6395	.0724	3.035	3.324	2.0	5.0
	national	38	2.921	.8893	.1443	2.629	3.213	.0	4.0
	club	19	2.158	.9582	.2198	1.696	2.620	.0	4.0
	Total	135	2.963	.8345	.0718	2.821	3.105	.0	5.0
legext	international	78	3.282	.7712	.0873	3.108	3.456	1.0	5.0
	national	38	2.776	.8028	.1302	2.512	3.040	.0	4.0
	club	19	2.342	.9436	.2165	1.887	2.797	.0	4.0
	Total	135	3.007	.8724	.0751	2.859	3.156	.0	5.0
forlean	international	78	1.282	.8626	.0977	1.088	1.477	.0	4.0
	national	38	1.382	.9331	.1514	1.075	1.688	.0	3.0
	club	19	1.684	.7493	.1719	1.323	2.045	1.0	3.0
	Total	135	1.367	.8729	.0751	1.218	1.515	.0	4.0
changefl	international	78	.160	.4868	.0551	.051	.270	.0	3.0
	national	38	.158	.3874	.0628	.031	.285	.0	1.5
	club	19	.789	1.0317	.2367	.292	1.287	.0	4.0
	Total	135	.248	.6074	.0523	.145	.352	.0	4.0

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
trunkrot	international	78	2.795	.6715	.0760	2.643	2.946	1.0	4.0
	national	38	2.395	.6893	.1118	2.168	2.621	1.0	4.0
	club	19	1.763	.7522	.1726	1.401	2.126	.5	4.0
	Total	135	2.537	.7718	.0664	2.406	2.668	.5	4.0
pulaflex	international	78	3.513	.6977	.0790	3.356	3.670	2.0	5.0
	national	38	3.500	.7884	.1279	3.241	3.759	2.0	5.0
	club	19	3.000	.8819	.2023	2.575	3.425	1.0	4.0
	Total	135	3.437	.7664	.0660	3.307	3.568	1.0	5.0
pusaext	international	78	2.487	.5753	.0651	2.357	2.617	1.0	3.0
	national	38	2.711	.7501	.1217	2.464	2.957	1.0	4.0
	club	19	2.605	.8910	.2044	2.176	3.035	1.0	4.0
	Total	135	2.567	.6797	.0585	2.451	2.682	1.0	4.0
pusahi	international	78	3.442	.8678	.0983	3.247	3.638	.0	5.0
	national	38	3.368	.7136	.1158	3.134	3.603	2.0	4.0
	club	19	2.553	1.3006	.2984	1.926	3.179	.5	5.0
	Total	135	3.296	.9449	.0813	3.135	3.457	.0	5.0
headmot	international	78	.718	.6008	.0680	.582	.853	.0	2.0
	national	38	.763	.7420	.1204	.519	1.007	.0	2.5
	club	19	1.105	.9941	.2281	.626	1.584	.0	3.0
	Total	135	.785	.7138	.0614	.664	.907	.0	3.0
boatmot	international	78	1.308	.6656	.0754	1.158	1.458	.0	4.0
	national	38	1.724	.8676	.1407	1.439	2.009	.0	4.0
	club	19	2.684	1.2158	.2789	2.098	3.270	.5	4.0
	Total	135	1.619	.9388	.0808	1.459	1.778	.0	4.0

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
strokew	international	78	2.923	.6982	.0791	2.766	3.081	1.0	4.0
	national	38	2.500	.6678	.1083	2.281	2.719	1.0	3.5
	club	19	2.053	.6213	.1425	1.753	2.352	1.0	3.0
	Total	135	2.681	.7447	.0641	2.555	2.808	1.0	4.0
grip	international	78	2.410	.7802	.0883	2.234	2.586	1.0	4.0
	national	38	2.658	.9380	.1522	2.350	2.966	1.0	4.0
	club	19	2.289	.7325	.1680	1.936	2.643	1.0	4.0
	Total	135	2.463	.8255	.0710	2.322	2.603	1.0	4.0
bladent	international	78	1.705	.5124	.0580	1.590	1.821	1.0	3.0
	national	38	1.855	.4637	.0752	1.703	2.008	1.0	3.0
	club	19	2.237	.4821	.1106	2.004	2.469	1.5	3.0
	Total	135	1.822	.5236	.0451	1.733	1.911	1.0	3.0
p_to_v	international	78	2.038	.7506	.0850	1.869	2.208	1.0	4.0
	national	38	2.303	.6832	.1108	2.078	2.527	1.0	4.5
	club	19	3.184	.7676	.1761	2.814	3.554	2.0	4.0
	Total	135	2.274	.8257	.0711	2.134	2.415	1.0	4.5
kneeprox	international	78	1.974	.3594	.0407	1.893	2.055	1.0	3.0
	national	38	2.368	.6439	.1045	2.157	2.580	.0	3.0
	club	19	2.684	.8201	.1881	2.289	3.079	.0	4.0
	Total	135	2.185	.5914	.0509	2.085	2.286	.0	4.0
bounce	international	78	1.019	.6469	.0732	.873	1.165	.0	4.0
	national	38	1.513	.8890	.1442	1.221	1.805	.0	4.0
	club	19	2.184	1.3459	.3088	1.536	2.833	.0	4.0
	Total	135	1.322	.9334	.0803	1.163	1.481	.0	4.0

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
rock	international	78	1.218	.5732	.0649	1.089	1.347	.0	3.0
	national	38	1.526	.7794	.1264	1.270	1.782	.0	3.5
	club	19	2.658	1.2589	.2888	2.051	3.265	.5	4.0
	Total	135	1.507	.8977	.0773	1.355	1.660	.0	4.0
arm_leg	international	78	1.654	.5052	.0572	1.540	1.768	1.0	3.0
	national	38	2.039	.6915	.1122	1.812	2.267	.0	3.5
	club	19	2.789	.9177	.2105	2.347	3.232	.0	4.0
	Total	135	1.922	.7378	.0635	1.797	2.048	.0	4.0
foreach	international	78	2.974	.7020	.0795	2.816	3.133	2.0	5.0
	national	38	2.579	.7581	.1230	2.330	2.828	1.0	4.0
	club	19	2.211	.8550	.1961	1.798	2.623	1.0	4.0
	Total	135	2.756	.7867	.0677	2.622	2.889	1.0	5.0
bareach	international	78	2.295	.7405	.0838	2.128	2.462	1.0	4.0
	national	38	2.553	.8913	.1446	2.260	2.846	1.0	4.0
	club	19	2.579	.6925	.1589	2.245	2.913	1.0	4.0
	Total	135	2.407	.7851	.0676	2.274	2.541	1.0	4.0

gender = male, distance = 200

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
spm	international	16	68.9206	3.36895	.84224	67.1254	70.7158	65.22	75.00
	national	7	60.6457	4.71351	1.78154	56.2864	65.0050	55.55	68.18
	Total	23	66.4022	5.38090	1.12199	64.0753	68.7290	55.55	75.00
stime	international	16	.8725	.04187	.01047	.8502	.8948	.80	.92
	national	7	.9943	.07458	.02819	.9253	1.0633	.88	1.08
	Total	23	.9096	.07743	.01615	.8761	.9430	.80	1.08
ptime	international	16	.4800	.05266	.01317	.4519	.5081	.40	.56
	national	7	.4914	.09155	.03460	.4068	.5761	.36	.60
	Total	23	.4835	.06485	.01352	.4554	.5115	.36	.60
gtime	international	16	.3925	.04892	.01223	.3664	.4186	.32	.48
	national	7	.5029	.08281	.03130	.4263	.5794	.36	.60
	Total	23	.4261	.07873	.01642	.3920	.4601	.32	.60
ptage	international	16	55.3944	4.97950	1.24487	52.7410	58.0478	45.45	63.64
	national	7	49.3629	8.13572	3.07501	41.8386	56.8871	37.50	60.87
	Total	23	53.5587	6.55821	1.36748	50.7227	56.3947	37.50	63.64
gtage	international	16	44.6063	4.98083	1.24521	41.9522	47.2603	36.36	54.56
	national	7	50.6371	8.13572	3.07501	43.1129	58.1614	39.13	62.50
	Total	23	46.4417	6.55877	1.36760	43.6055	49.2780	36.36	62.50
time	international	16	38.94825	.561098	.140275	38.64926	39.24724	38.073	40.027
	national	7	43.70429	3.152295	1.191455	40.78890	46.61967	39.840	48.510
	Total	23	40.39574	2.816294	.587238	39.17788	41.61360	38.073	48.510

a. gender = male, distance = 200

gender = male, distance = 500

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
spm	international	30	60.4947	3.22543	.58888	59.2903	61.6991	51.72	65.22
	national	22	56.2864	3.57575	.76235	54.7010	57.8718	51.72	62.50
	club	9	50.2344	4.90386	1.63462	46.4650	54.0039	44.12	57.69
	Total	61	57.4631	5.06466	.64846	56.1660	58.7602	44.12	65.22
stime	international	30	.9947	.05532	.01010	.9740	1.0153	.92	1.16
	national	22	1.0700	.06640	.01416	1.0406	1.0994	.96	1.16
	club	9	1.2044	.11566	.03855	1.1155	1.2934	1.04	1.36
	Total	61	1.0528	.10027	.01284	1.0271	1.0785	.92	1.36
ptime	international	30	.5580	.06110	.01116	.5352	.5808	.48	.72
	national	22	.6145	.06147	.01311	.5873	.6418	.52	.72
	club	9	.6356	.09262	.03087	.5644	.7067	.52	.84
	Total	61	.5898	.07290	.00933	.5712	.6085	.48	.84
gtime	international	30	.4367	.05683	.01038	.4154	.4579	.32	.56
	national	22	.4582	.04447	.00948	.4385	.4779	.36	.56
	club	9	.5689	.06566	.02189	.5184	.6194	.48	.64
	Total	61	.4639	.06974	.00893	.4461	.4818	.32	.64
ptage	international	30	56.0933	5.18841	.94727	54.1560	58.0307	48.15	66.67
	national	22	57.4986	3.68293	.78520	55.8657	59.1316	51.72	65.38
	club	9	52.6700	4.30501	1.43500	49.3609	55.9791	48.15	61.76
	Total	61	56.0951	4.76567	.61018	54.8745	57.3156	48.15	66.67
gtage	international	30	43.9400	5.24411	.95744	41.9818	45.8982	33.33	52.85
	national	22	42.5014	3.68293	.78520	40.8684	44.1343	34.62	48.28
	club	9	47.3300	4.30501	1.43500	44.0209	50.6391	38.24	51.85
	Total	61	43.9213	4.79508	.61395	42.6932	45.1494	33.33	52.85

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
time	international	30	98.77117	4.533678	.827733	97.07826	100.46407	92.945	109.534
	national	22	113.72455	7.729347	1.647902	110.29755	117.15155	103.390	129.240
	club	9	134.37556	8.417137	2.805712	127.90557	140.84554	121.390	146.710
	Total	61	109.41730	14.042818	1.797999	105.82076	113.01383	92.945	146.710

a. gender = male, distance = 500

gender = female, distance = 200

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
spm	international	9	64.0611	5.41384	1.80461	59.8997	68.2226	57.69	75.00
	national	4	58.9350	2.99175	1.49587	54.1745	63.6955	55.55	62.50
	club	3	57.2067	4.68984	2.70768	45.5564	68.8569	53.57	62.50
	Total	16	61.4944	5.45262	1.36316	58.5889	64.3999	53.57	75.00
stime	international	9	.9422	.07513	.02504	.8845	1.0000	.80	1.04
	national	4	1.0200	.05164	.02582	.9378	1.1022	.96	1.08
	club	3	1.0533	.08327	.04807	.8465	1.2602	.96	1.12
	Total	16	.9825	.08258	.02065	.9385	1.0265	.80	1.12

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
ptime	international	9	.4667	.05292	.01764	.4260	.5073	.40	.56
	national	4	.5500	.02000	.01000	.5182	.5818	.52	.56
	club	3	.5333	.06110	.03528	.3816	.6851	.48	.60
	Total	16	.5000	.06022	.01506	.4679	.5321	.40	.60
gtime	international	9	.4756	.06766	.02255	.4235	.5276	.40	.60
	national	4	.4700	.03830	.01915	.4091	.5309	.44	.52
	club	3	.5200	.04000	.02309	.4206	.6194	.48	.56
	Total	16	.4825	.05745	.01436	.4519	.5131	.40	.60
ptage	international	9	49.6178	4.84133	1.61378	45.8964	53.3392	40.00	54.54
	national	4	53.9675	1.69997	.84998	51.2625	56.6725	51.85	56.00
	club	3	50.5733	2.75511	1.59066	43.7293	57.4174	48.15	53.57
	Total	16	50.8844	4.19611	1.04903	48.6484	53.1203	40.00	56.00
gtage	international	9	50.3822	4.84133	1.61378	46.6608	54.1036	45.46	60.00
	national	4	46.0325	1.69997	.84998	43.3275	48.7375	44.00	48.15
	club	3	49.4267	2.75511	1.59066	42.5826	56.2707	46.43	51.85
	Total	16	49.1156	4.19611	1.04903	46.8797	51.3516	44.00	60.00
time	international	9	44.44789	1.333963	.444654	43.42251	45.47326	42.674	45.450
	national	4	48.16500	3.613221	1.806611	42.41556	53.91444	43.020	51.450
	club	3	51.70000	3.433191	1.982154	43.17148	60.22852	49.560	55.660
	Total	16	46.73694	3.707528	.926882	44.76134	48.71254	42.674	55.660

a. gender = female, distance = 200

gender = female, distance = 500

Descriptives[a]

						95% Confidence Interval for Mean			
		N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum	Maximum
spm	international	23	57.4148	4.16477	.86841	55.6138	59.2158	48.39	62.50
	national	5	57.8280	3.16288	1.41448	53.9008	61.7552	53.57	62.50
	club	7	50.8571	4.89306	1.84940	46.3318	55.3825	45.45	60.00
	Total	35	56.1623	4.88765	.82616	54.4833	57.8413	45.45	62.50
stime	international	23	1.0504	.07836	.01634	1.0165	1.0843	.96	1.24
	national	5	1.0400	.05657	.02530	.9698	1.1102	.96	1.12
	club	7	1.1886	.10761	.04067	1.0890	1.2881	1.00	1.32
	Total	35	1.0766	.09816	.01659	1.0429	1.1103	.96	1.32
ptime	international	23	.5687	.04893	.01020	.5475	.5899	.50	.68
	national	5	.5680	.05933	.02653	.4943	.6417	.48	.64
	club	7	.5914	.05146	.01945	.5438	.6390	.54	.68
	Total	35	.5731	.05016	.00848	.5559	.5904	.48	.68
gtime	international	23	.4817	.04745	.00989	.4612	.5023	.40	.56
	national	5	.4720	.01789	.00800	.4498	.4942	.44	.48
	club	7	.5971	.11101	.04196	.4945	.6998	.44	.72
	Total	35	.5034	.07708	.01303	.4770	.5299	.40	.72
ptage	international	23	54.0652	2.74477	.57232	52.8783	55.2521	50.00	60.00
	national	5	54.5060	3.09195	1.38276	50.6668	58.3452	50.00	57.69
	club	7	50.0657	5.74599	2.17178	44.7516	55.3799	43.75	57.14
	Total	35	53.3283	3.81953	.64562	52.0162	54.6403	43.75	60.00
gtage	international	23	45.9348	2.74477	.57232	44.7479	47.1217	40.00	50.00
	national	5	45.4940	3.09195	1.38276	41.6548	49.3332	42.31	50.00
	club	7	49.9343	5.74599	2.17178	44.6201	55.2484	42.86	56.25
	Total	35	46.6717	3.81953	.64562	45.3597	47.9838	40.00	56.25

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
time	international	23	112.05600	6.692346	1.395451	109.16201	114.94999	103.690	127.032
	national	5	121.80600	5.961760	2.666180	114.40350	129.20850	117.040	131.870
	club	7	144.96429	4.733832	1.789220	140.58622	149.34235	134.740	148.790
	Total	35	120.03051	14.442787	2.441277	115.06924	124.99179	103.690	148.790

a. gender = female, distance = 500

Appendix B:

Electromyography results from Pilot Work

Figure B.1. EMG trace for the leg muscles for Subject 1 Trial 1

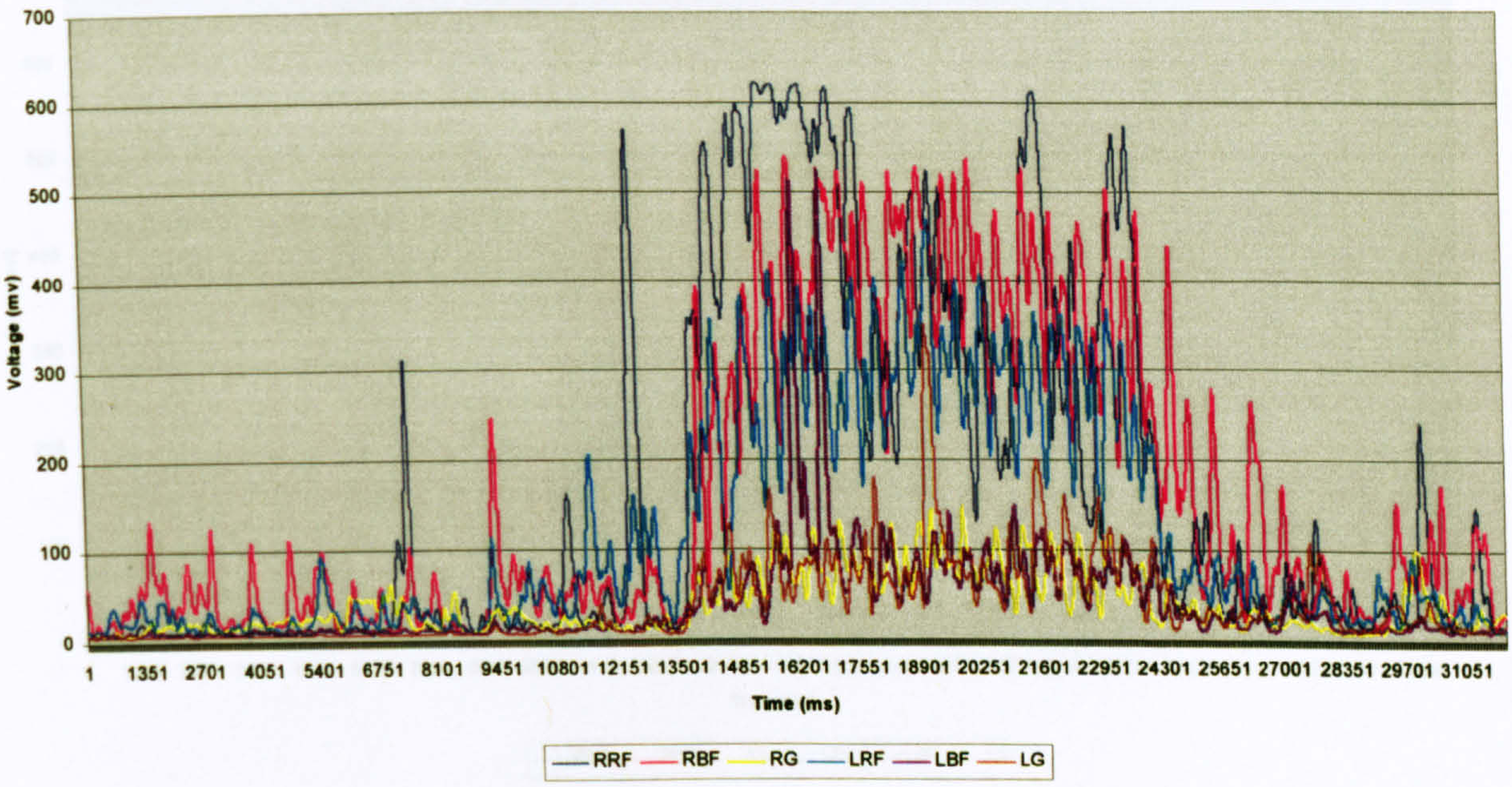


Figure B.2.EMG trace for the trunk muscles for Subject 1 Trial 1

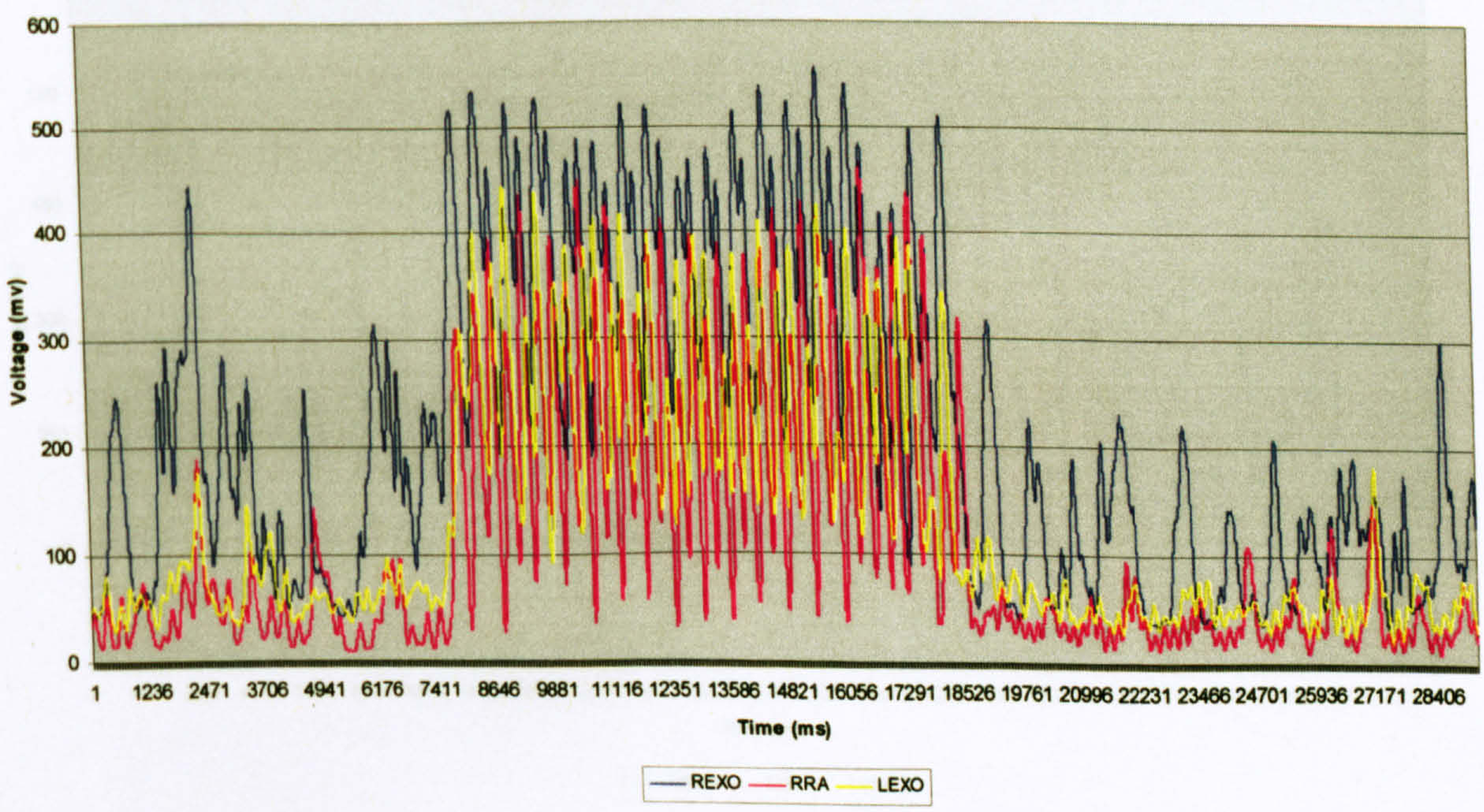


Figure B.3. EMG trace for the leg muscles for Subject 1 Trial 2

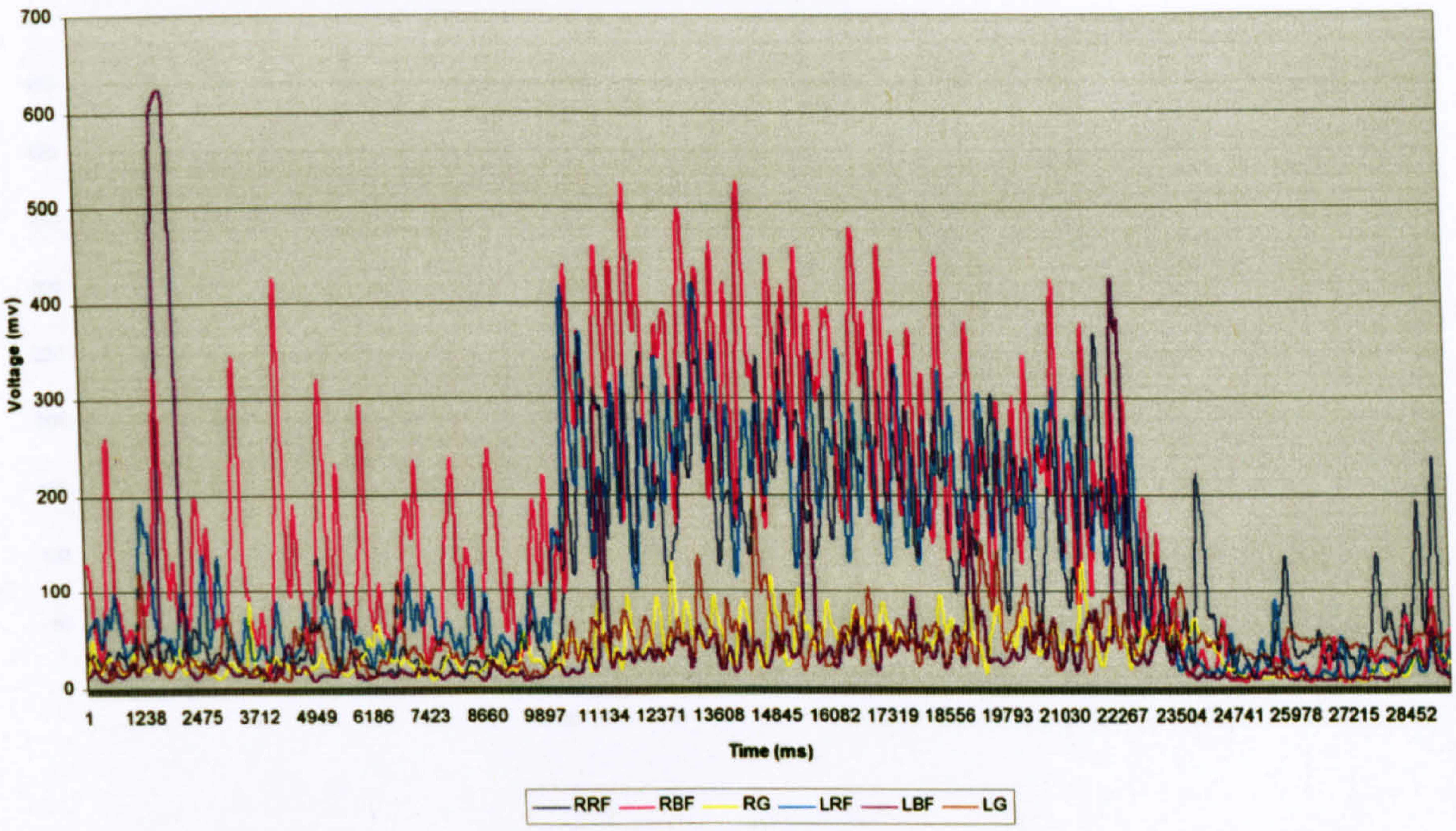


Figure B.4. EMG trace for the trunk muscles for Subject 1 Trial 2

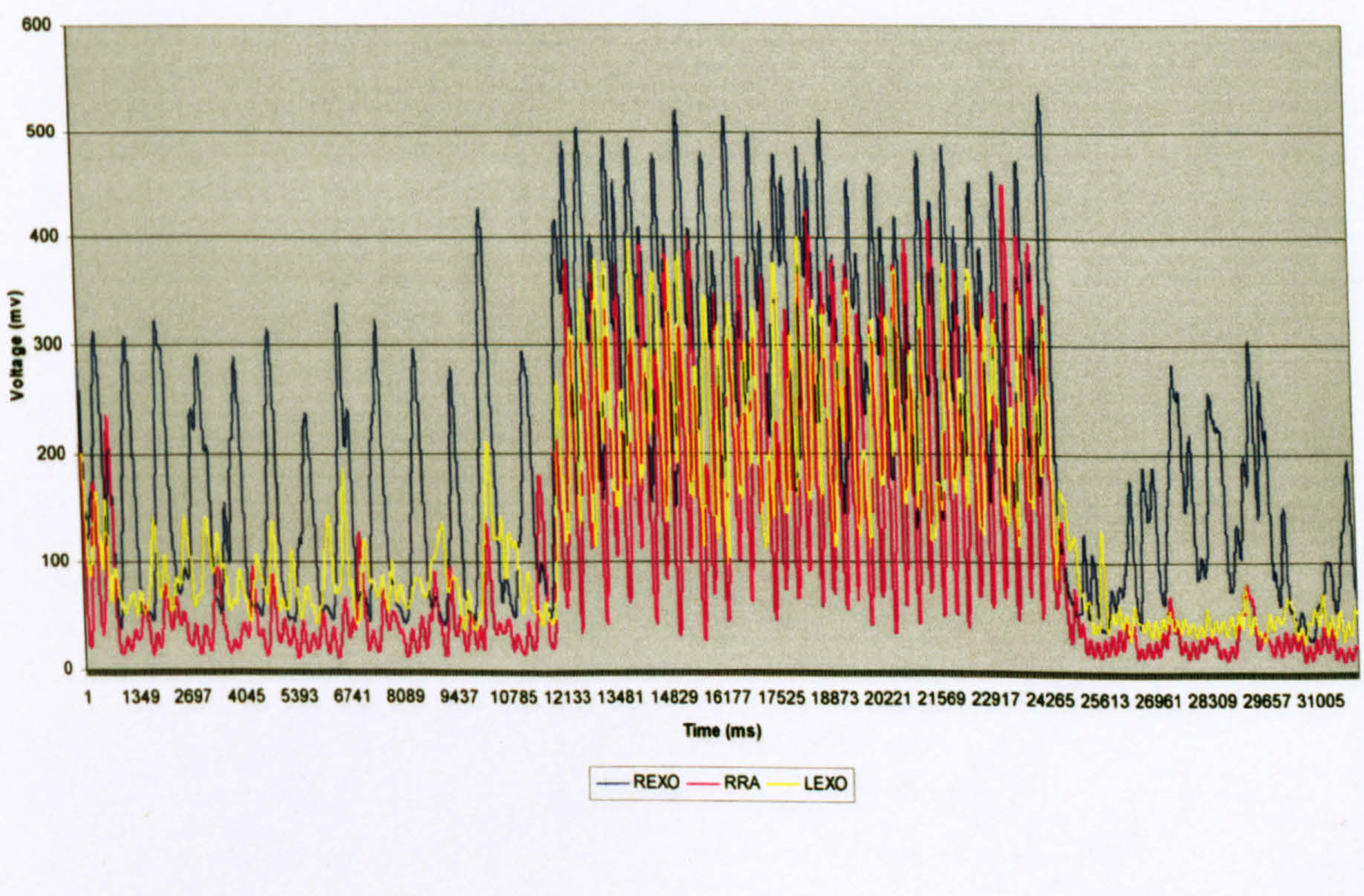


Figure B.5. EMG trace for the leg muscles for Subject 1 Trial 3

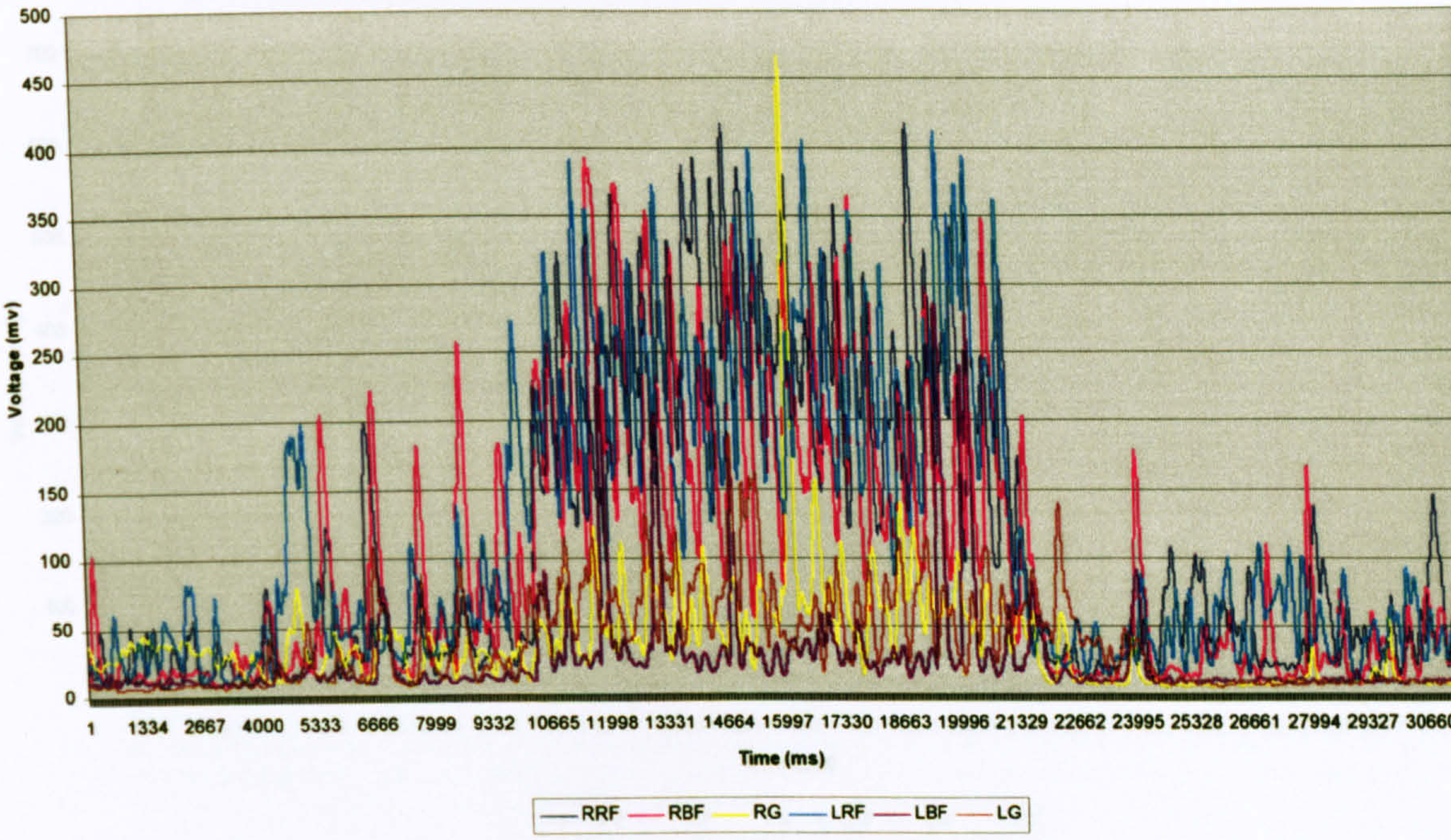


Figure B.6. EMG trace for the trunk muscles for Subject 1 Trial 3

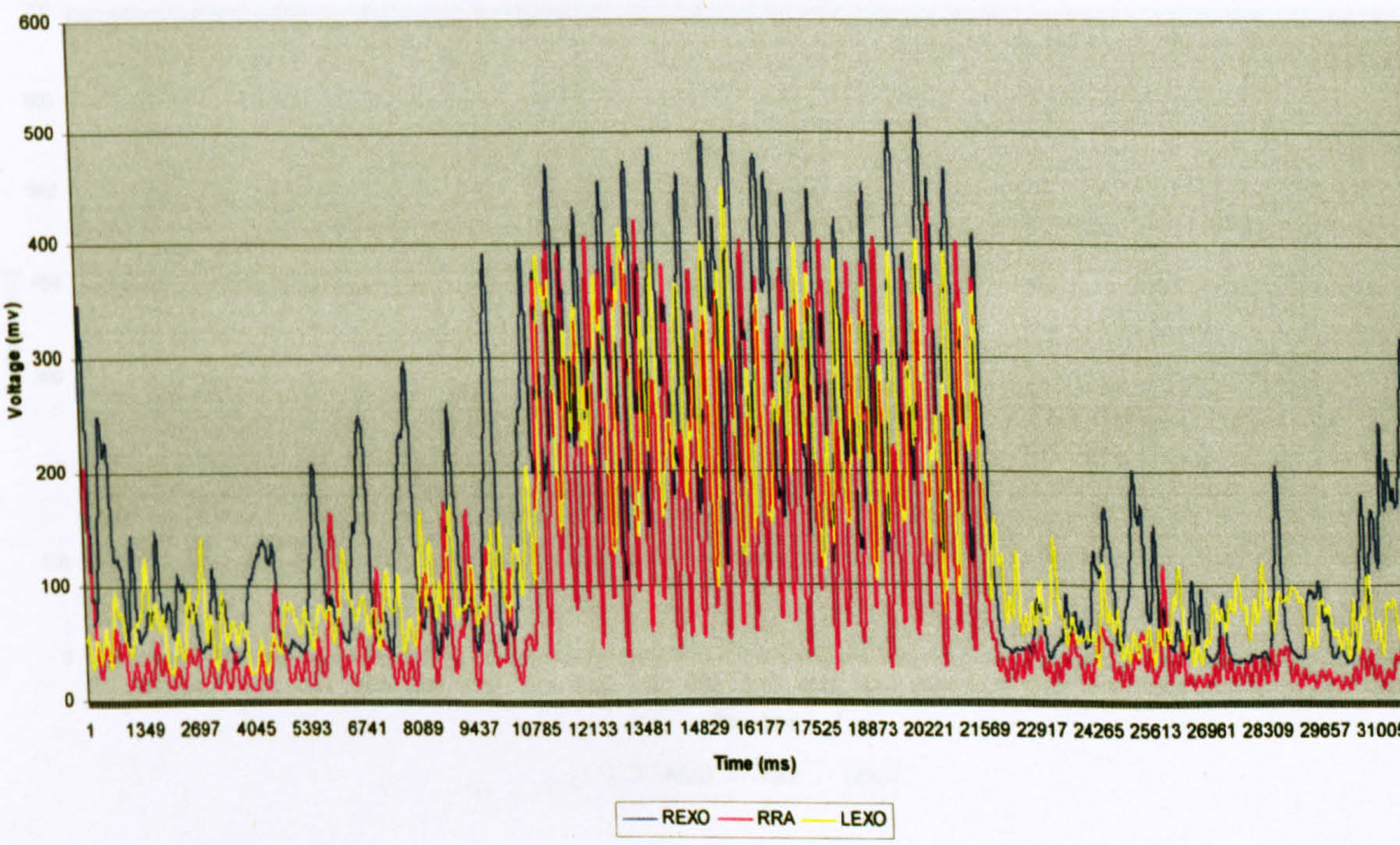


Figure B.7. EMG trace for the leg muscles for Subject 2 Trial 1

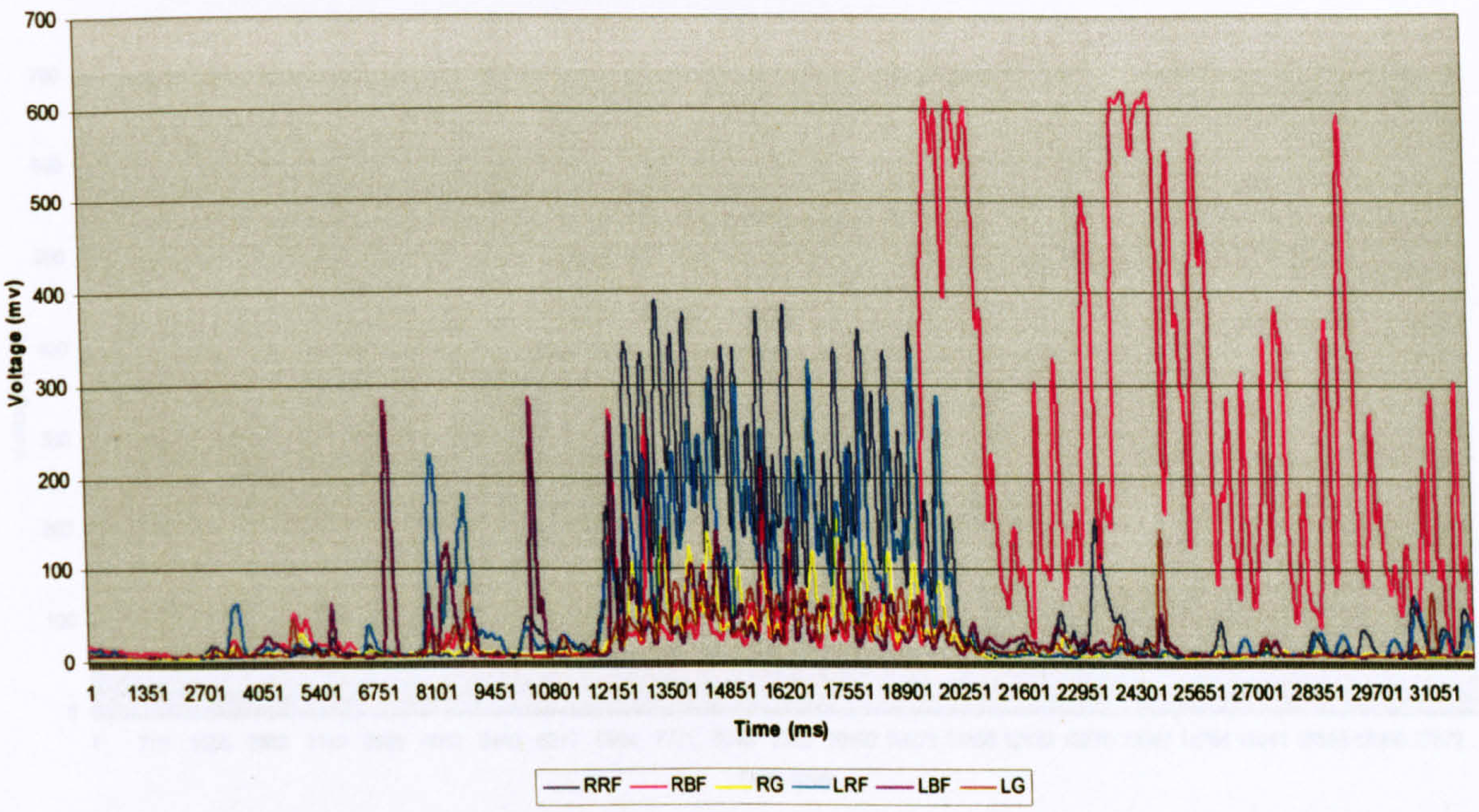


Figure B.8. EMG trace for the trunk muscles for Subject 2 Trial 1

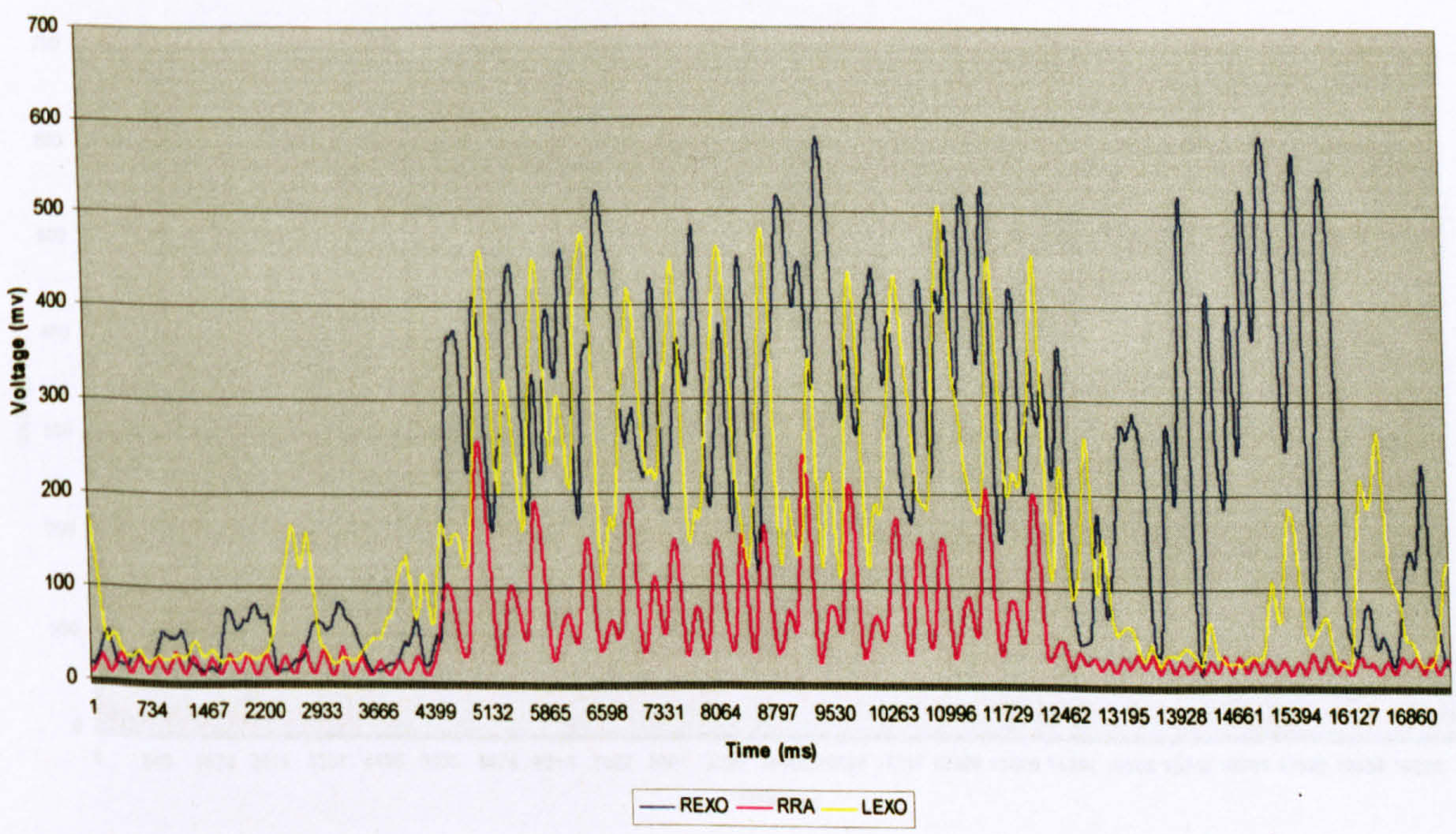


Figure B.9. EMG trace for the leg muscles for Subject 2 Trial 2

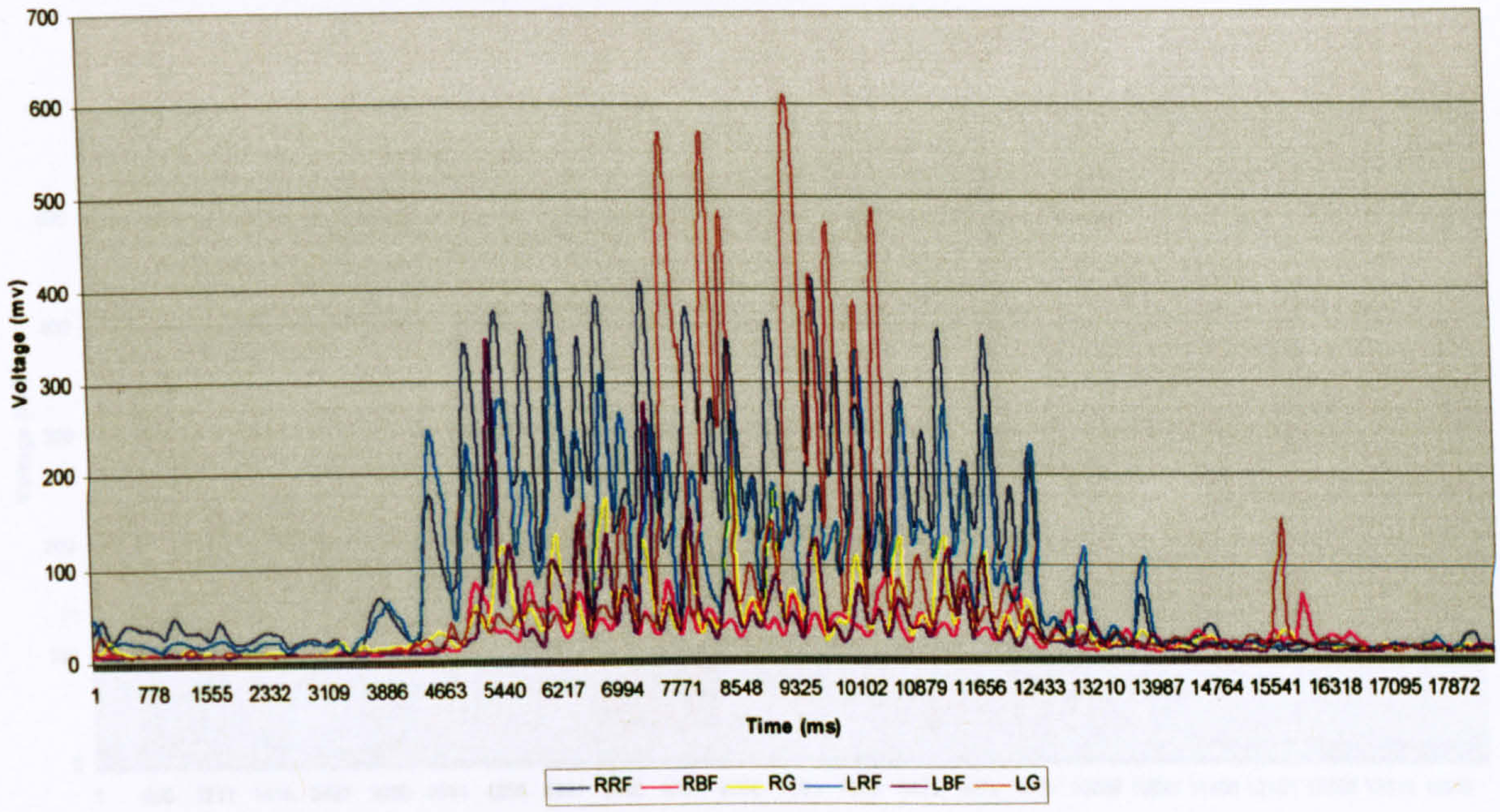


Figure B.10. EMG trace for the trunk muscles for Subject 2 Trial 2

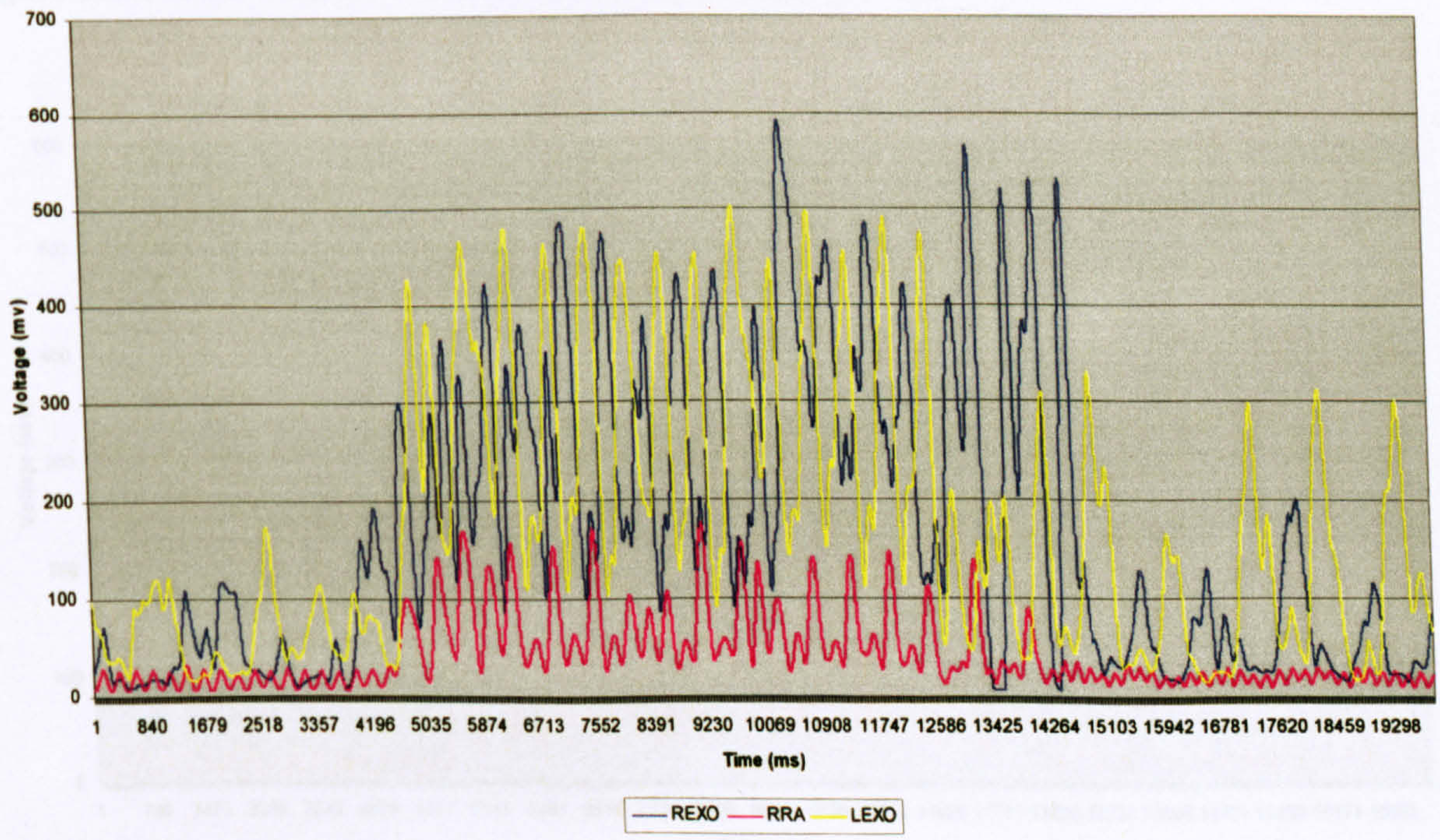


Figure B.11. EMG trace for the leg muscles for Subject 2 Trial 3

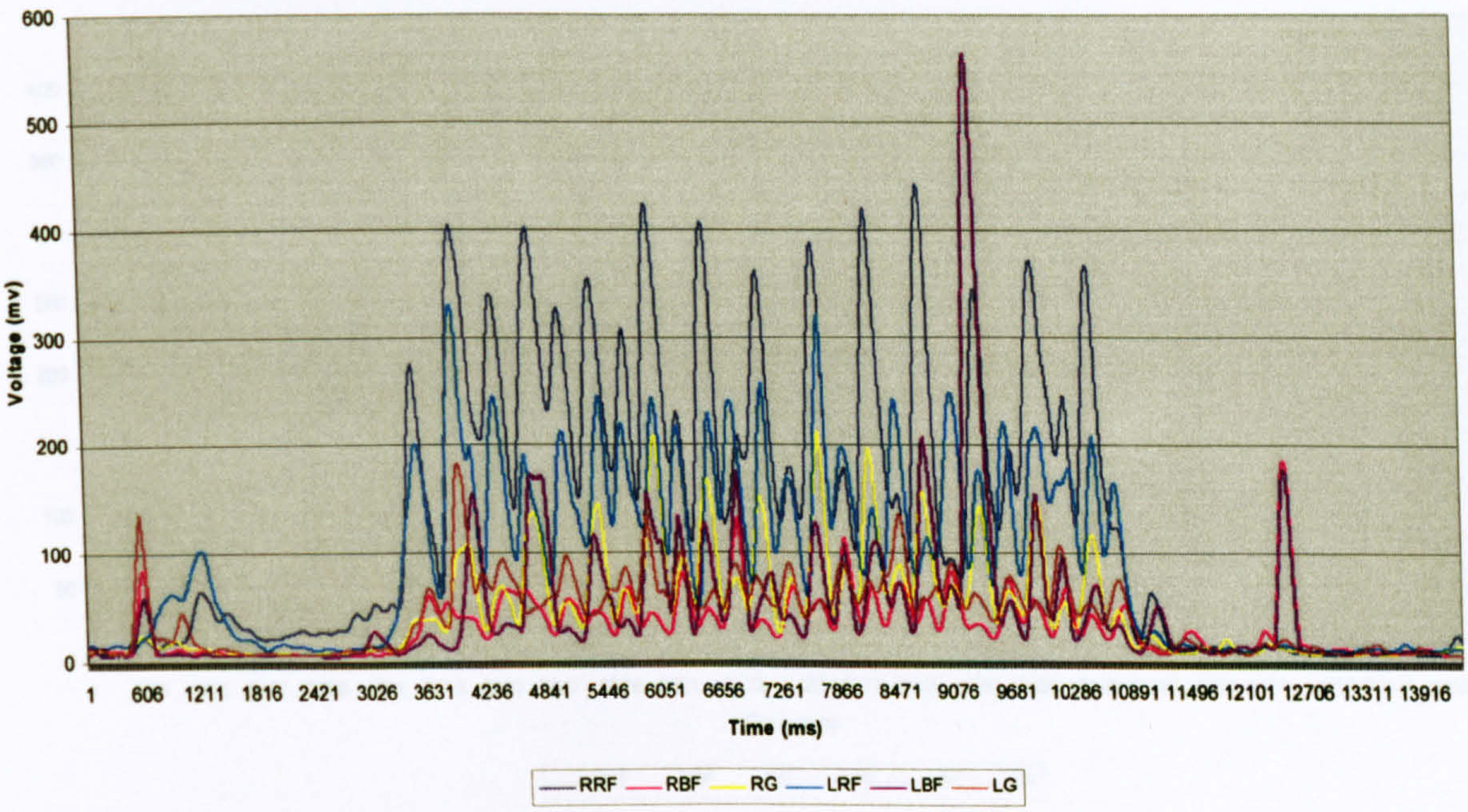


Figure B.12. EMG trace for the trunk muscles for Subject 2 Trial 3

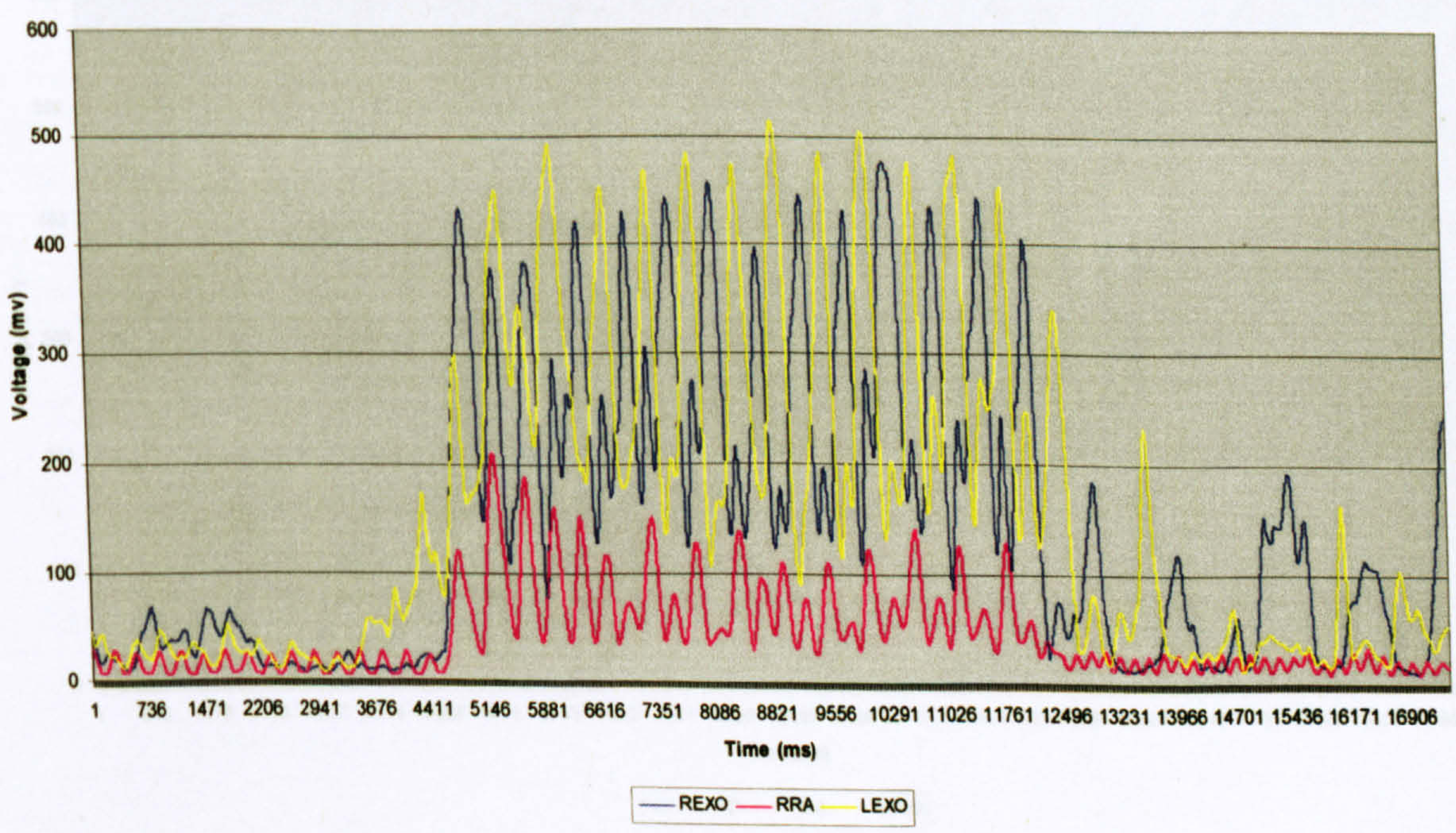


Figure B.13. EMG trace for the leg muscles for Subject 2 Trial 4

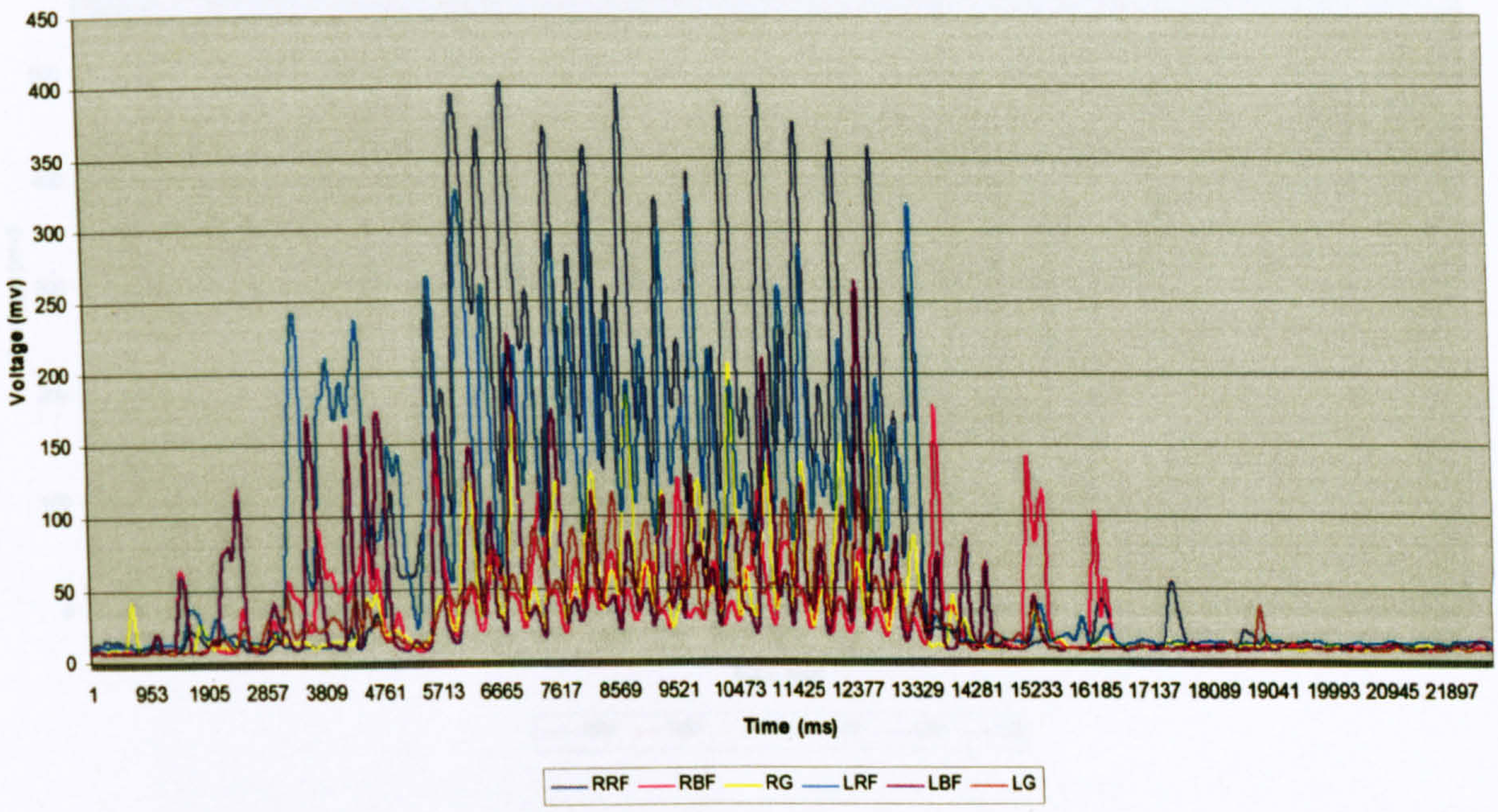


Figure B.14. EMG trace for the trunk muscles for Subject 2 Trial 4

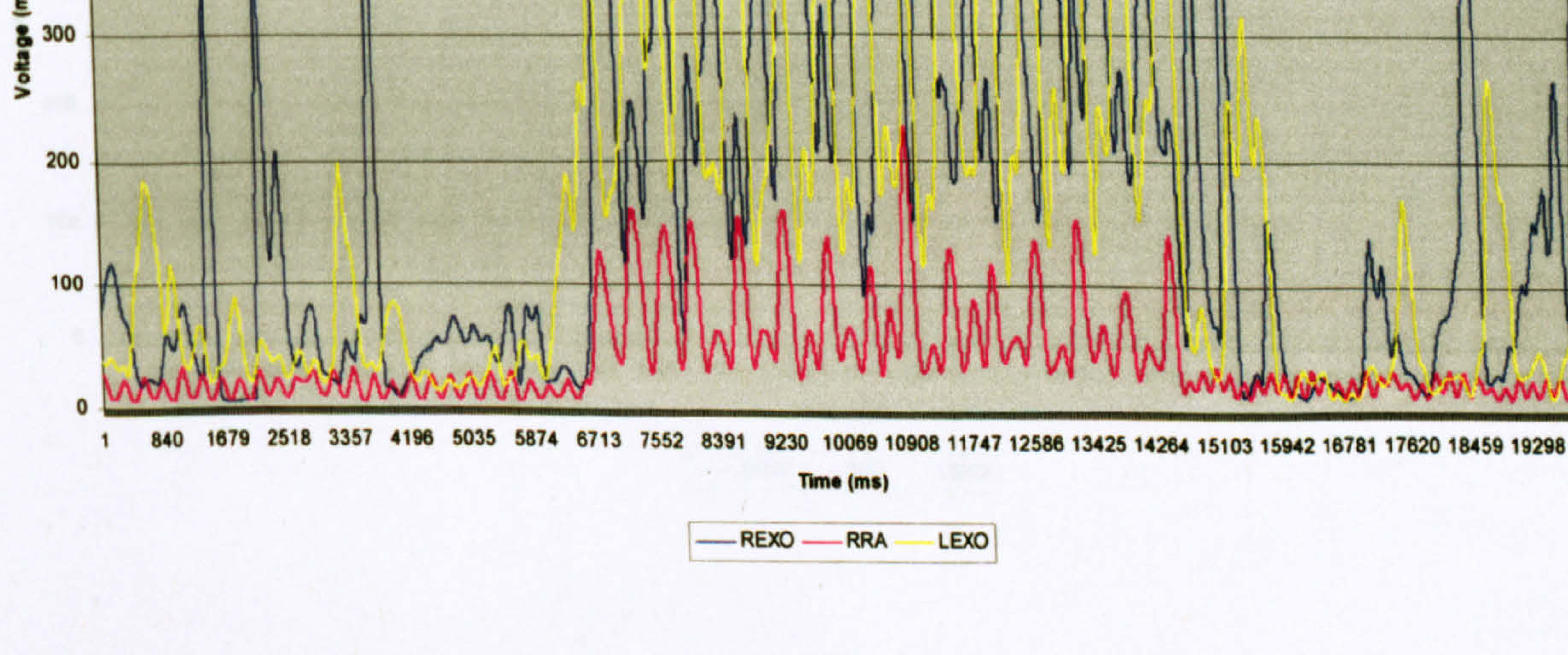


Figure B.15. EMG trace for the leg muscles for Subject 2 Trial 5

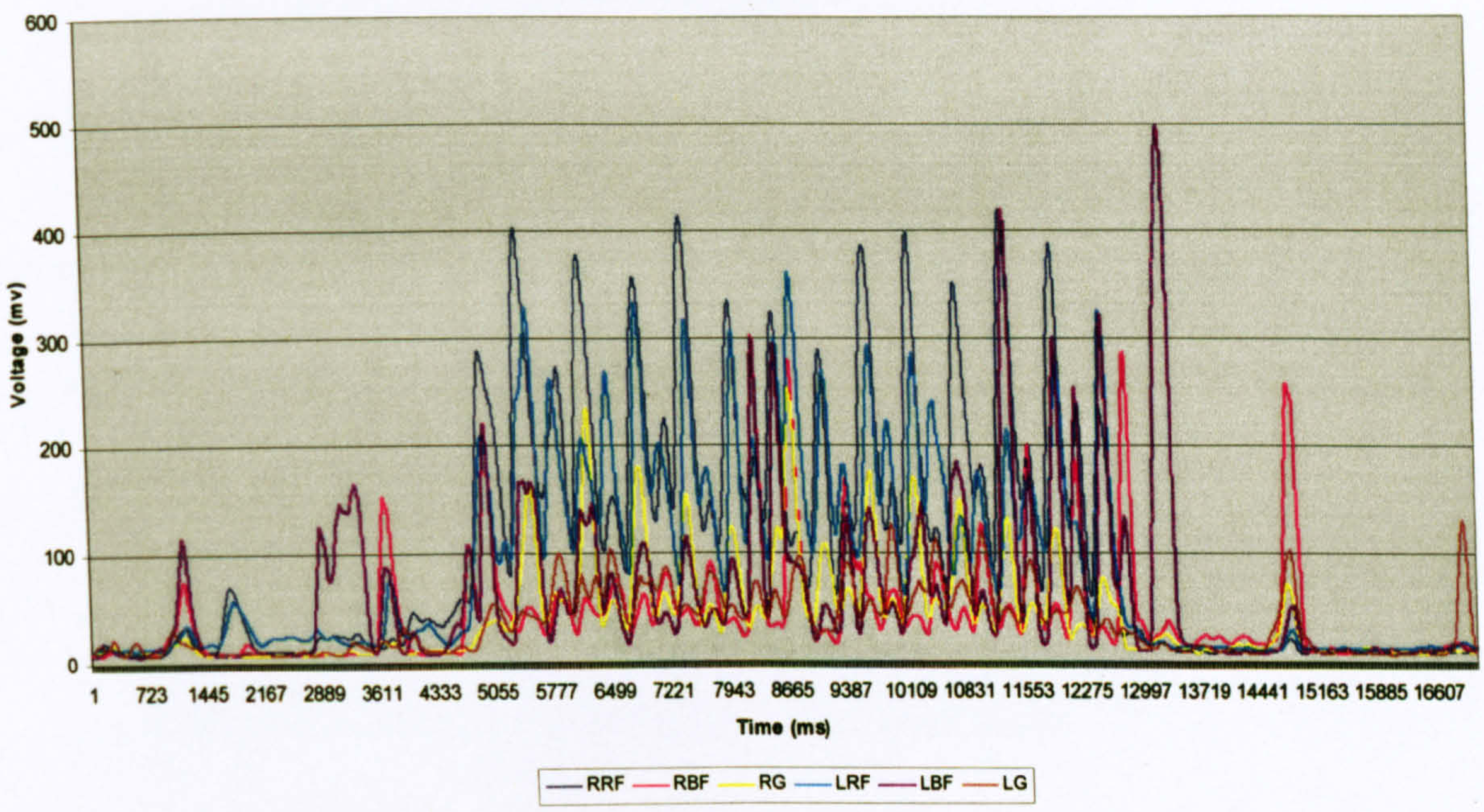
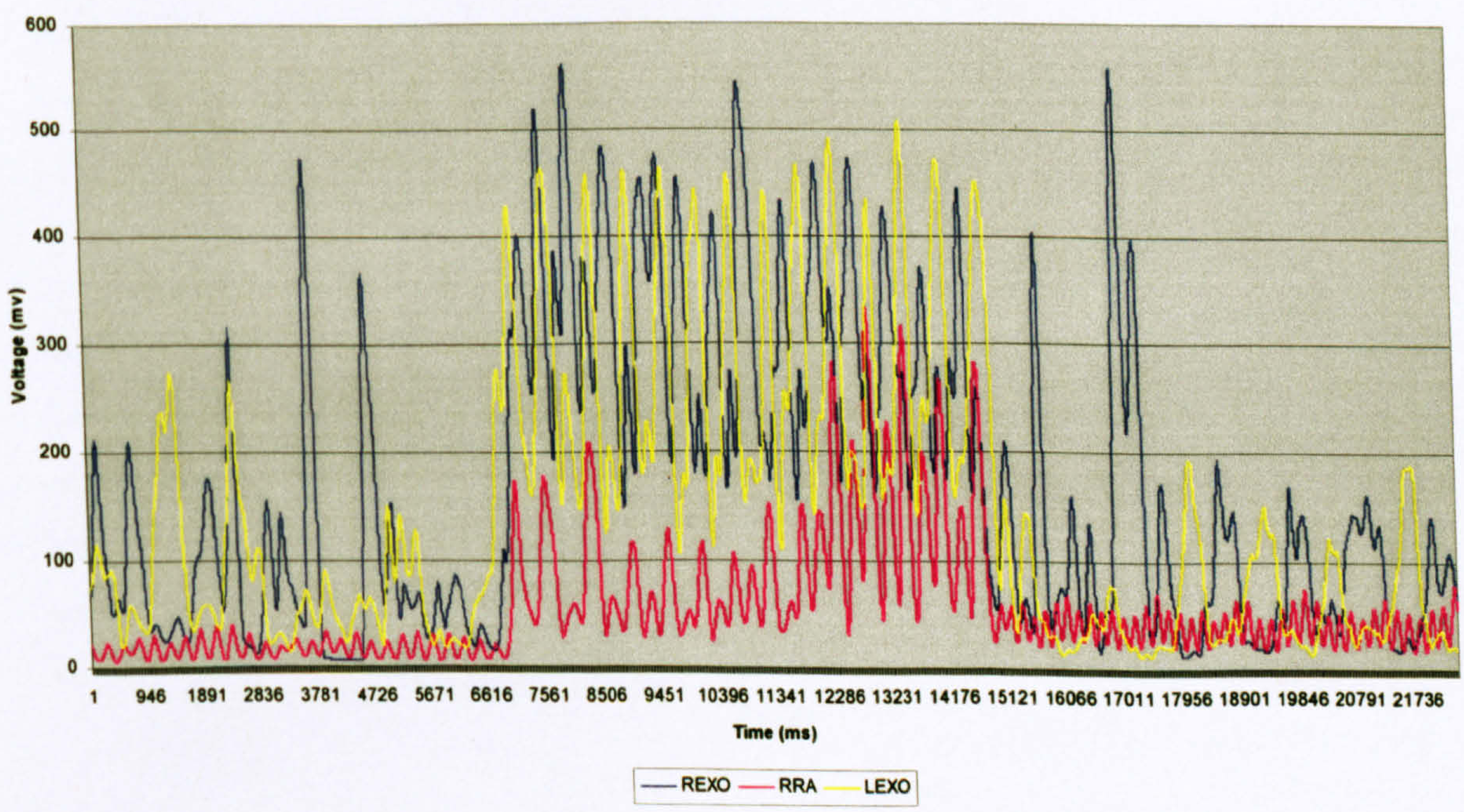


Figure B.16. EMG trace for the trunk muscles for Subject 2 Trial 5



Appendix C:

Electrogoniometer Accuracy Assessment Data

Goniometer 1 X-plane - Positive

Figure C.1. X-plane positive measure accuracy assessment of goniometer 1.

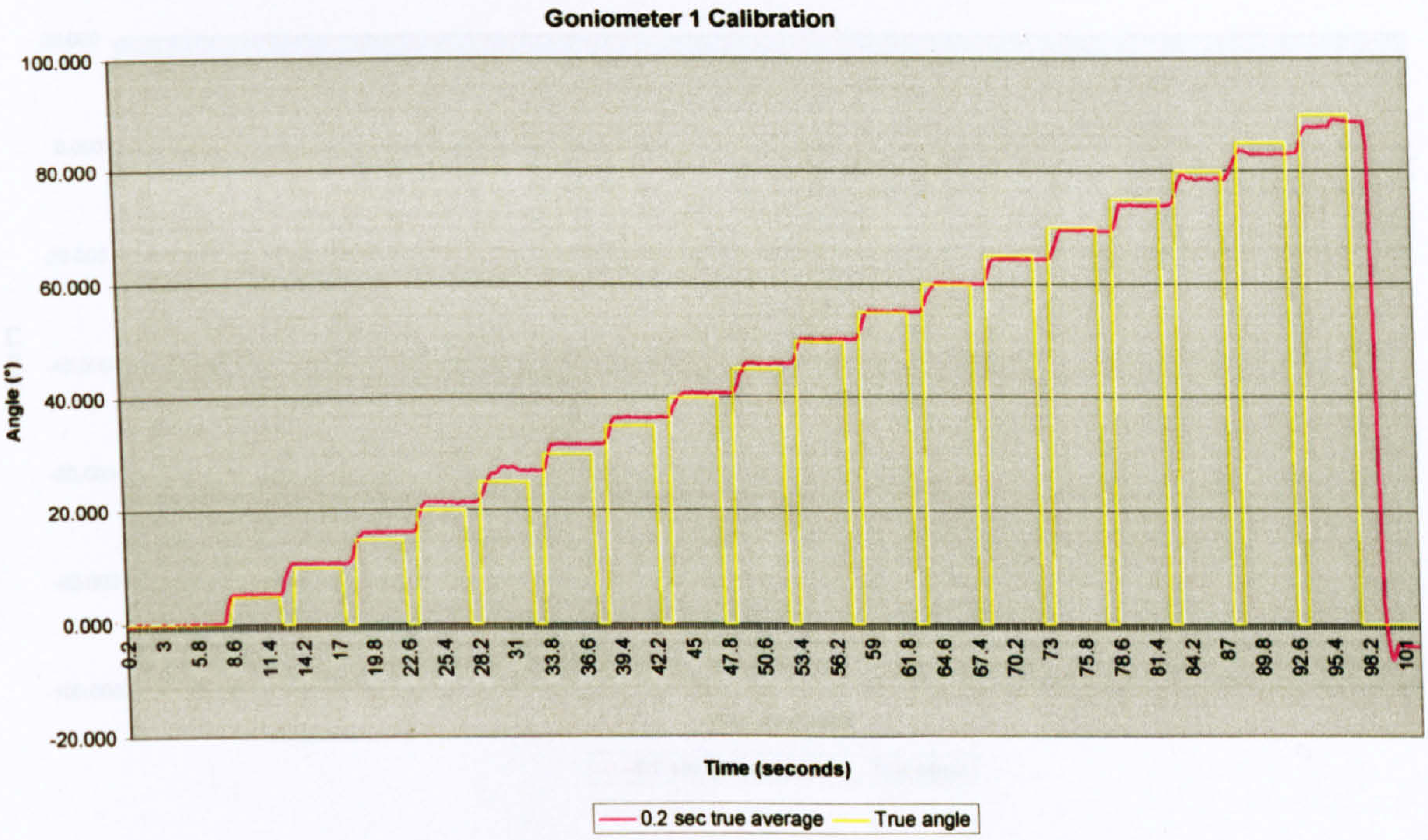
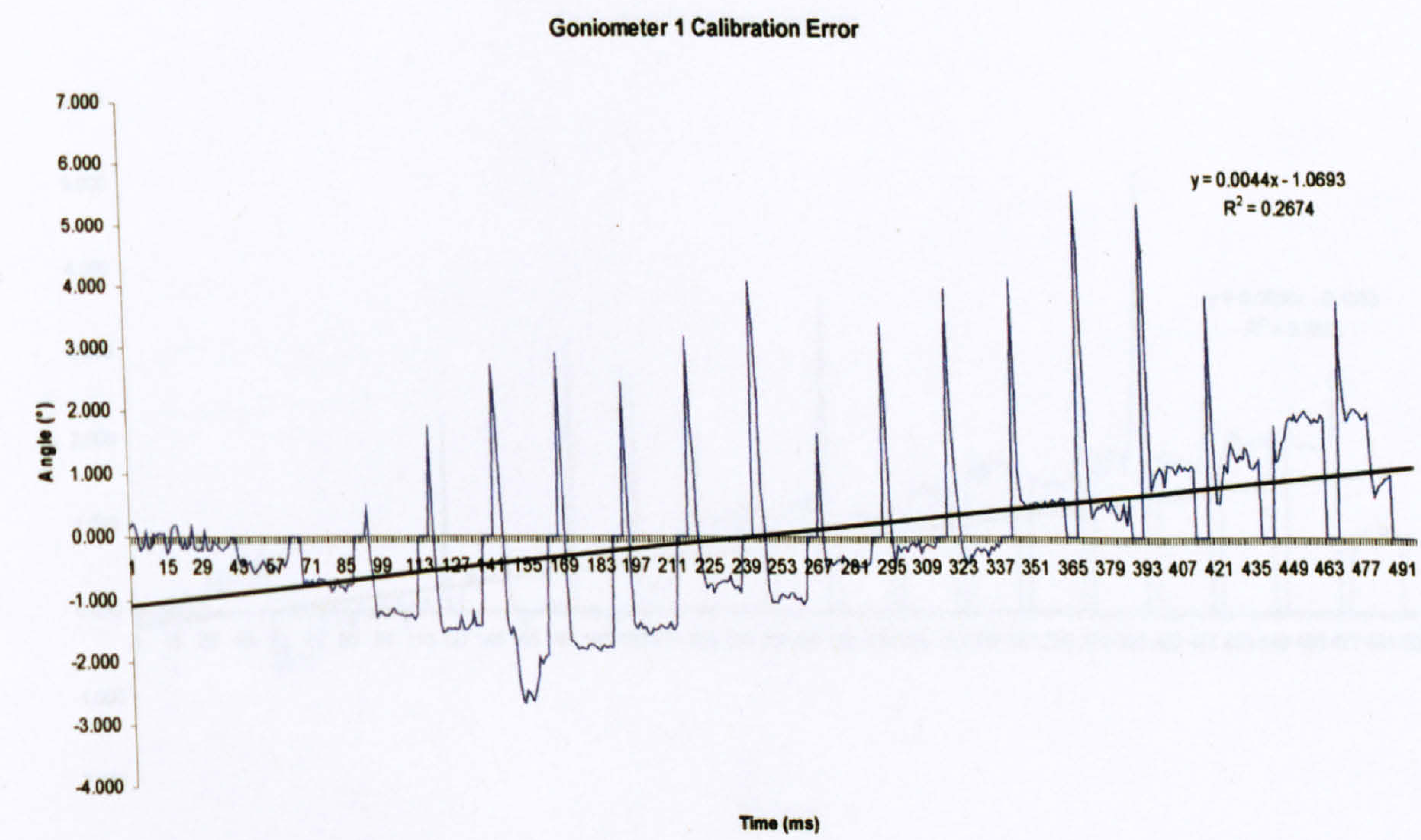


Figure C.2. Error identified in X-plane positive measure accuracy assessment of goniometer 1.



Goniometer 1 X-plane - Negative

Figure C.3. X-plane negative measure accuracy assessment of goniometer 1.

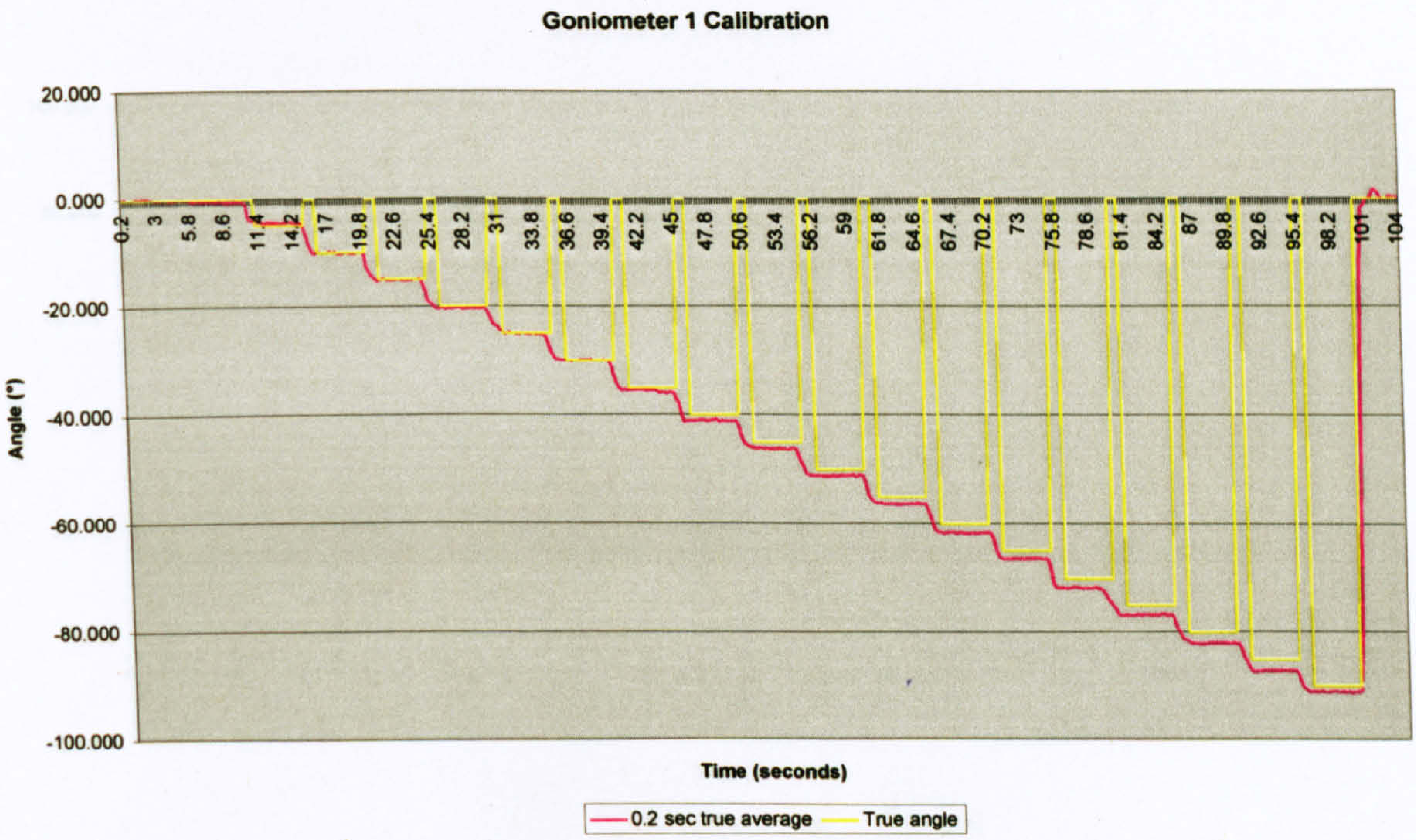
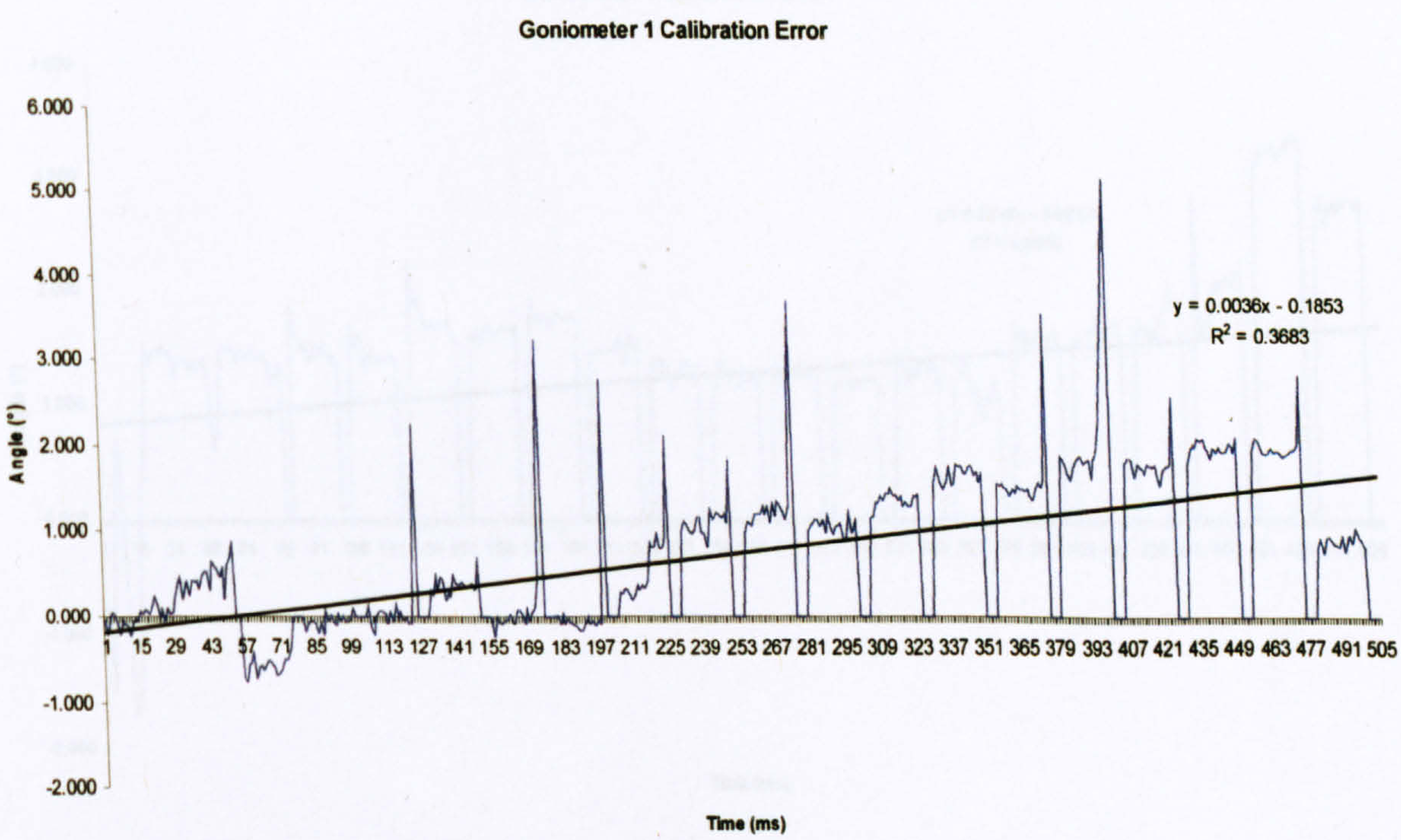


Figure C.4. Error identified in X-plane negative measure accuracy assessment of goniometer 1.



Goniometer 1 Calibration Y-plane - Positive

Figure C.5. Y-plane positive measure accuracy assessment of goniometer 1.

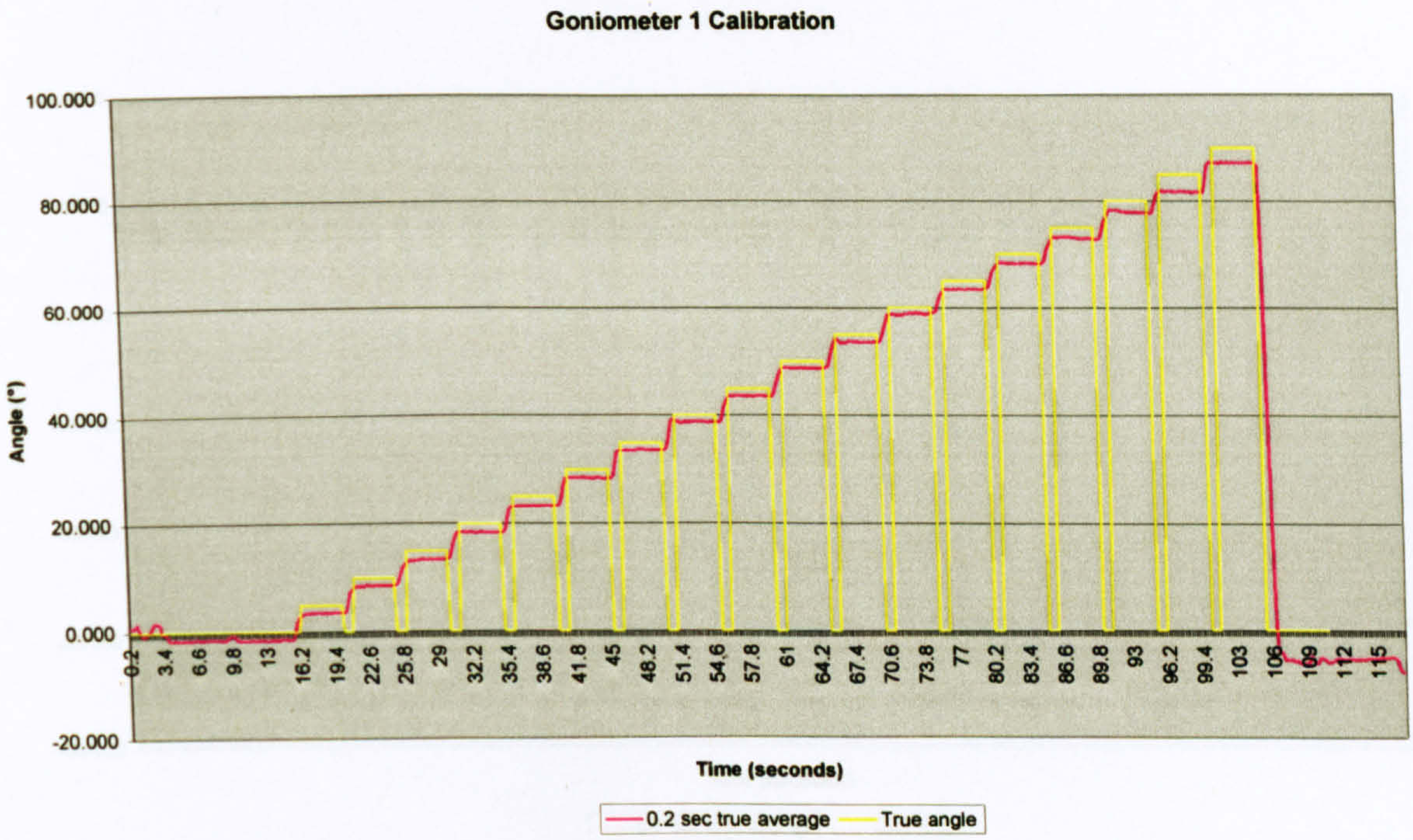
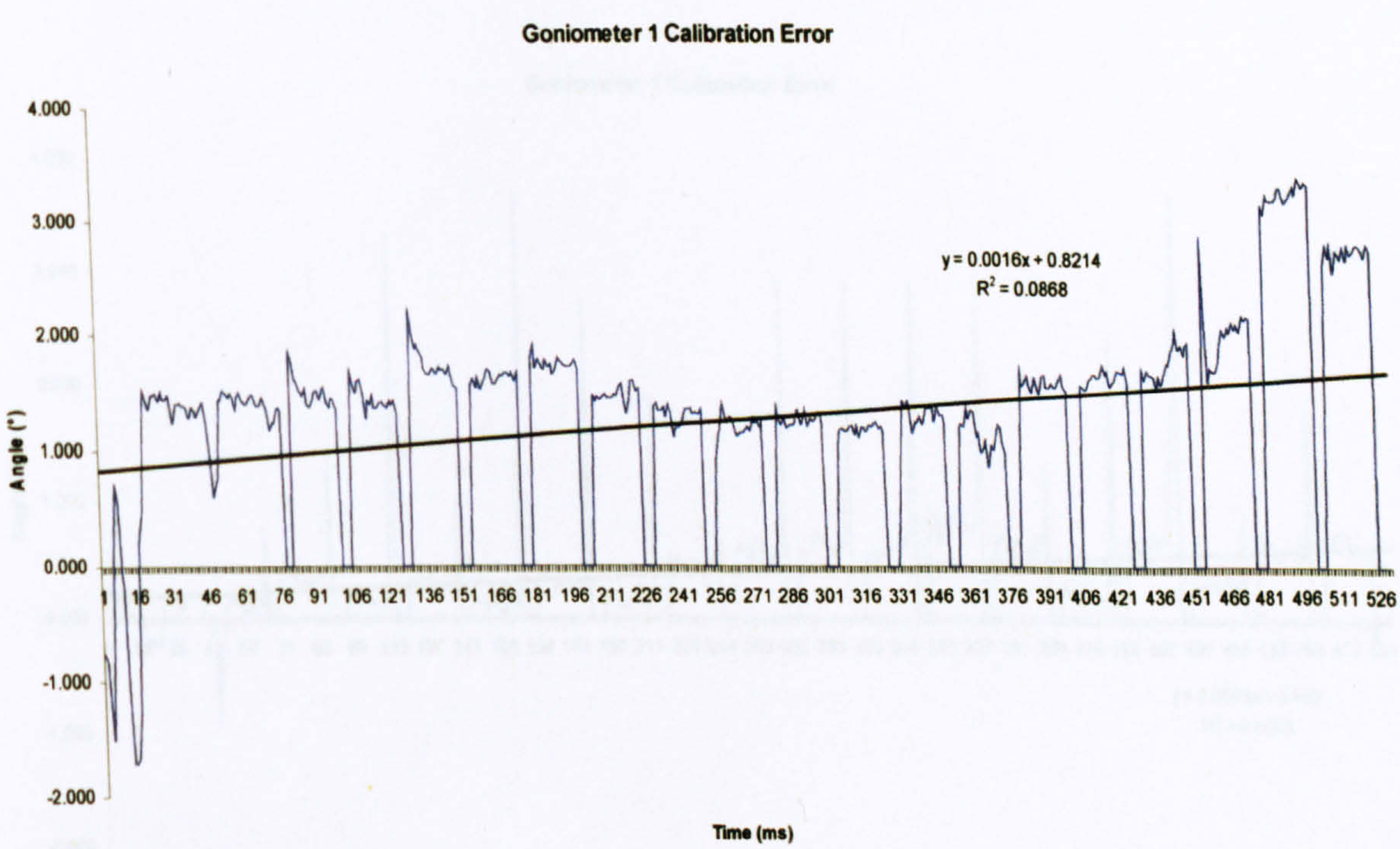


Figure C.6. Error identified in Y-plane positive measure accuracy assessment of goniometer 1.



Goniometer 1 Calibration Y-plane - Negative

Figure C.7. Y-plane negative measure accuracy assessment of goniometer 1.

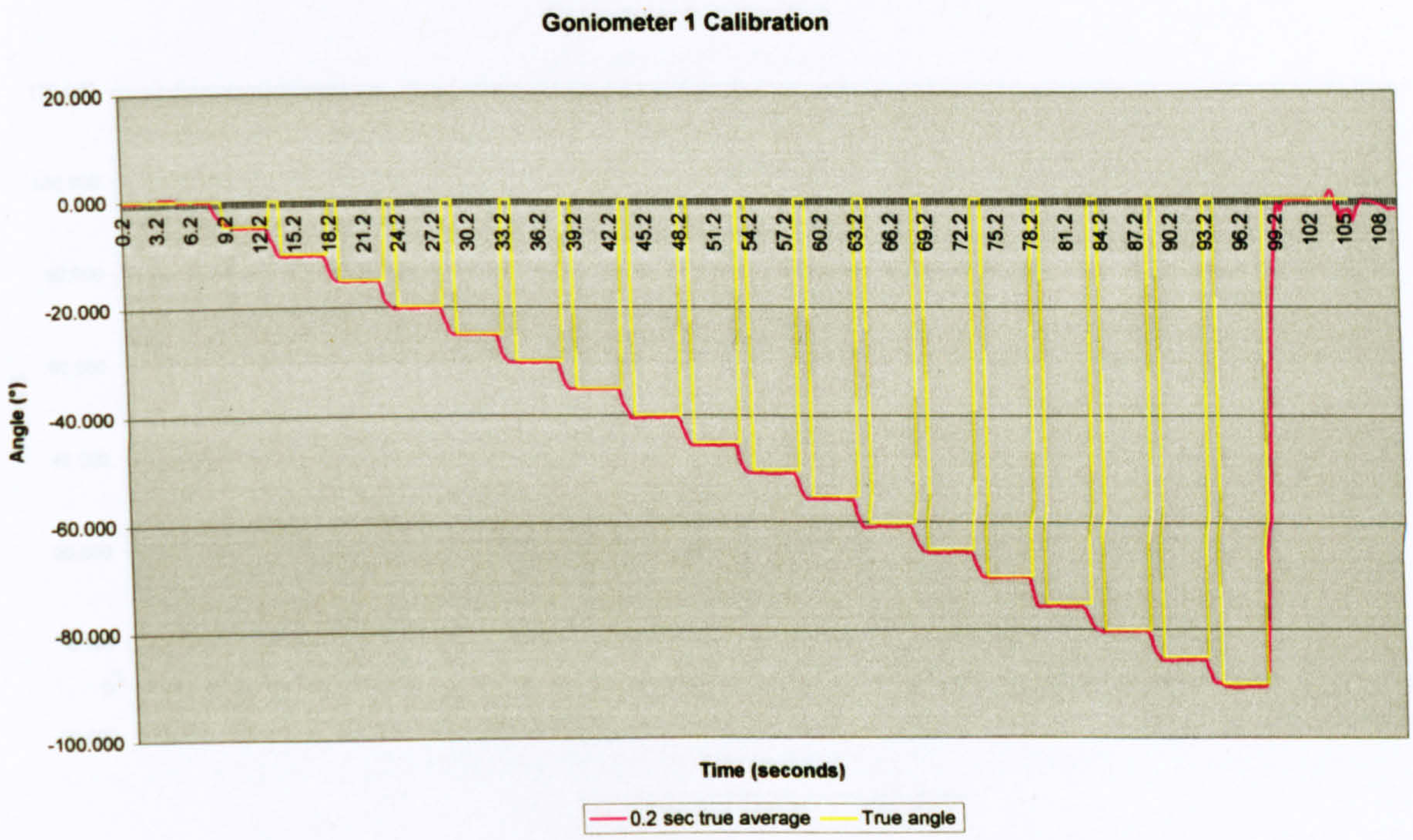
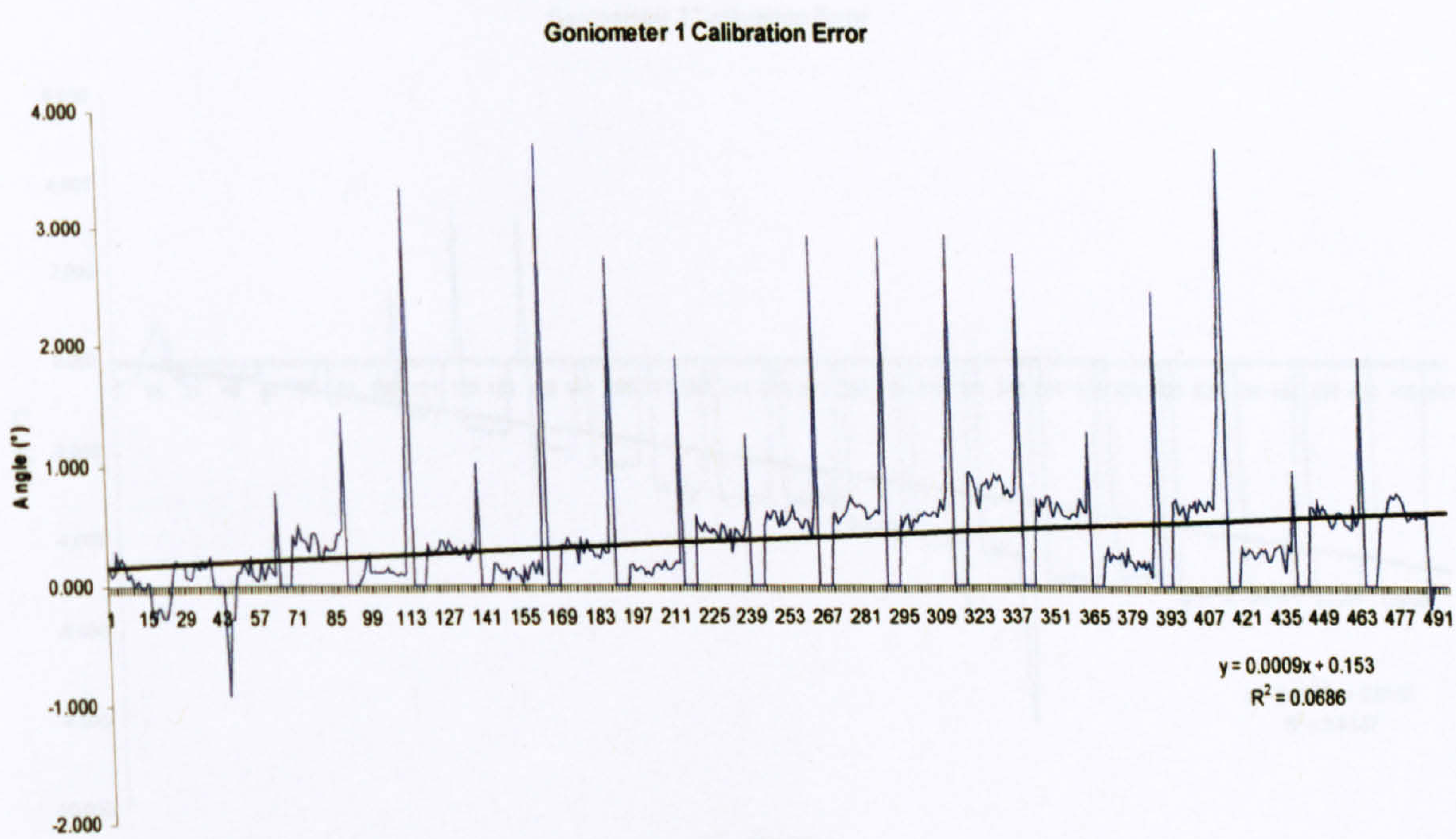


Figure C.8. Error identified in Y-plane negative measure accuracy assessment of goniometer 1.



Goniometer 2 X-plane Positive

Figure C.9. X-plane positive measure accuracy assessment of goniometer 2.

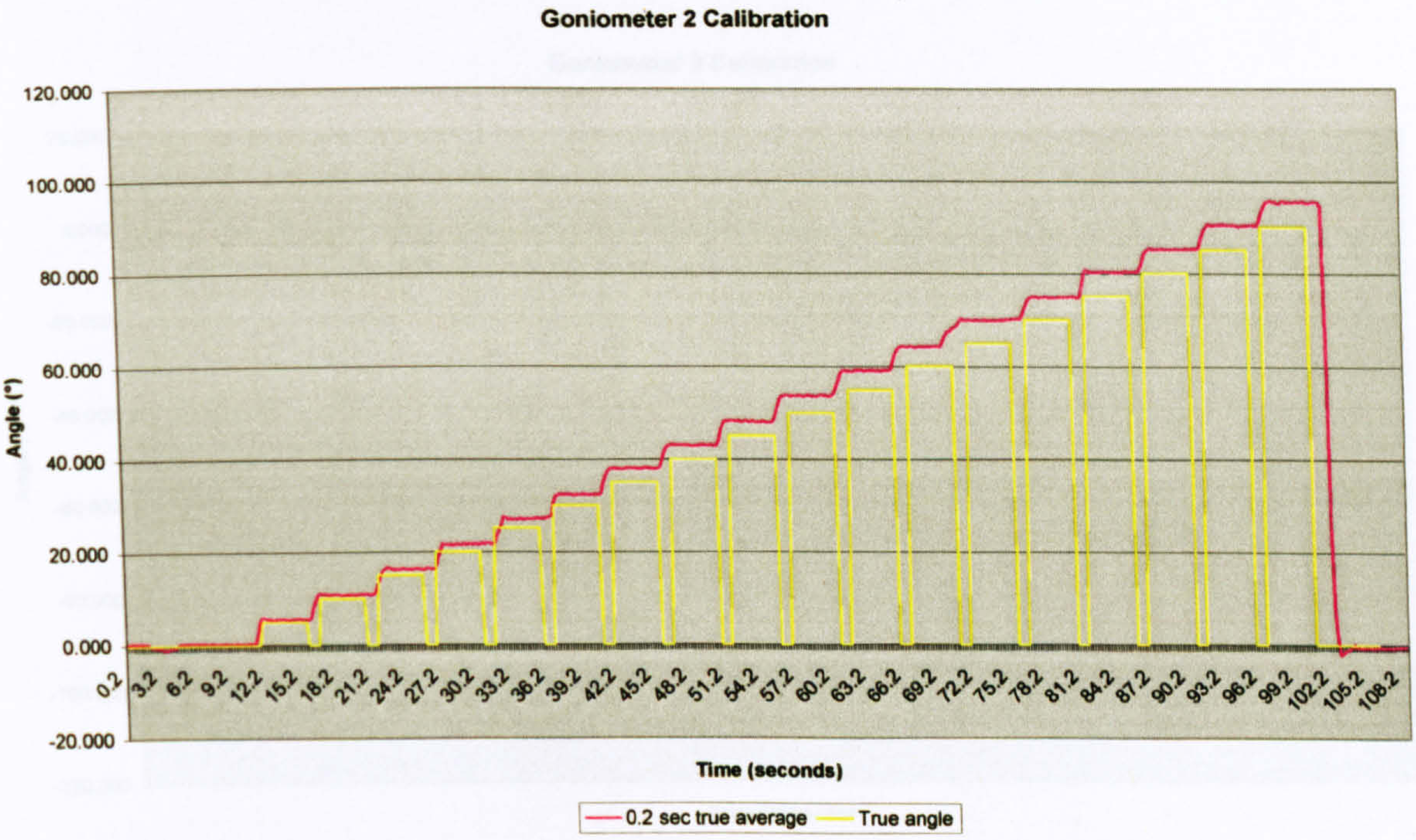
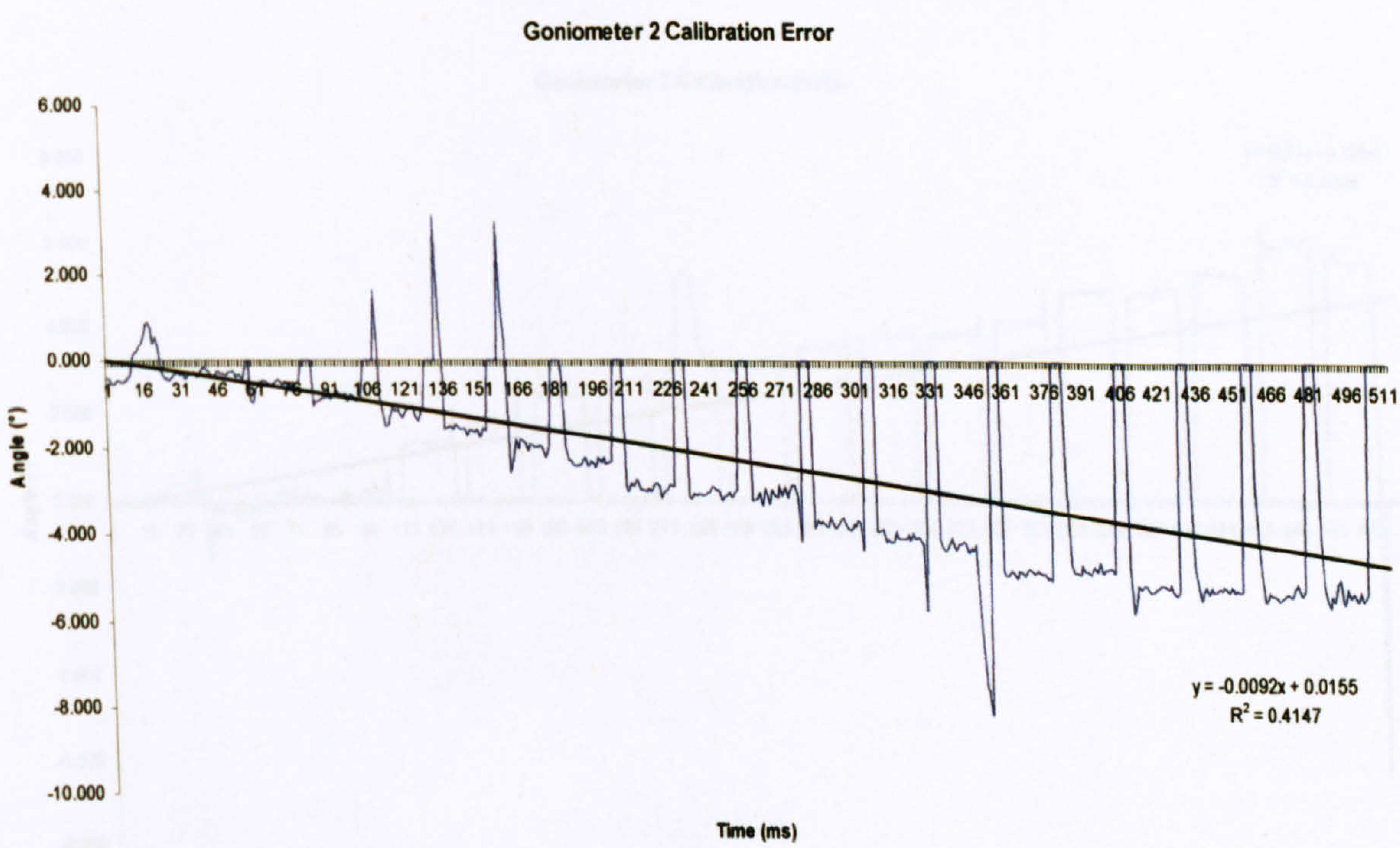


Figure C.10. Error identified in X-plane negative measure accuracy assessment of goniometer 2.



Goniometer 2 X-plane – Negative

Figure C.11. X-plane negative measure accuracy assessment of goniometer 2.

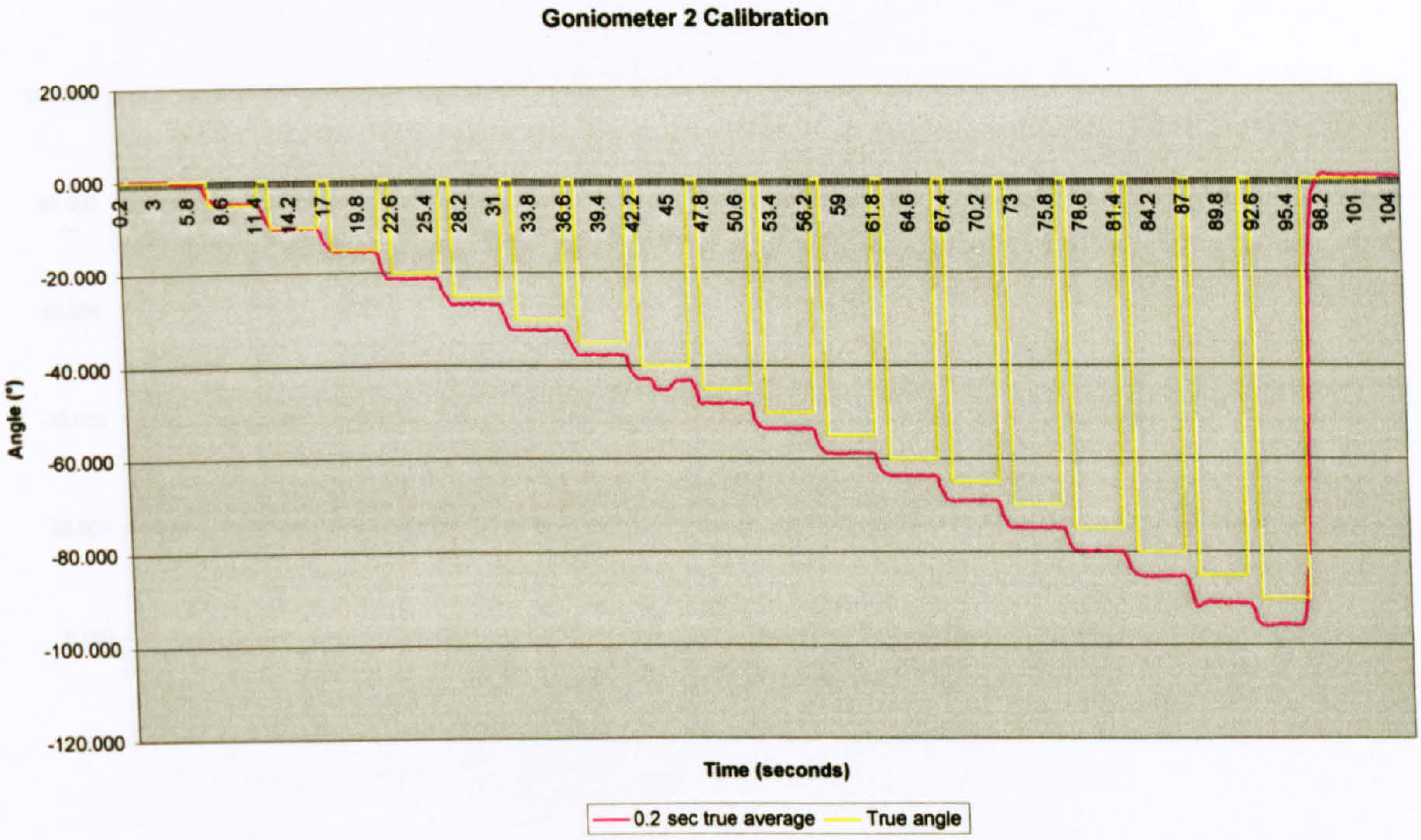
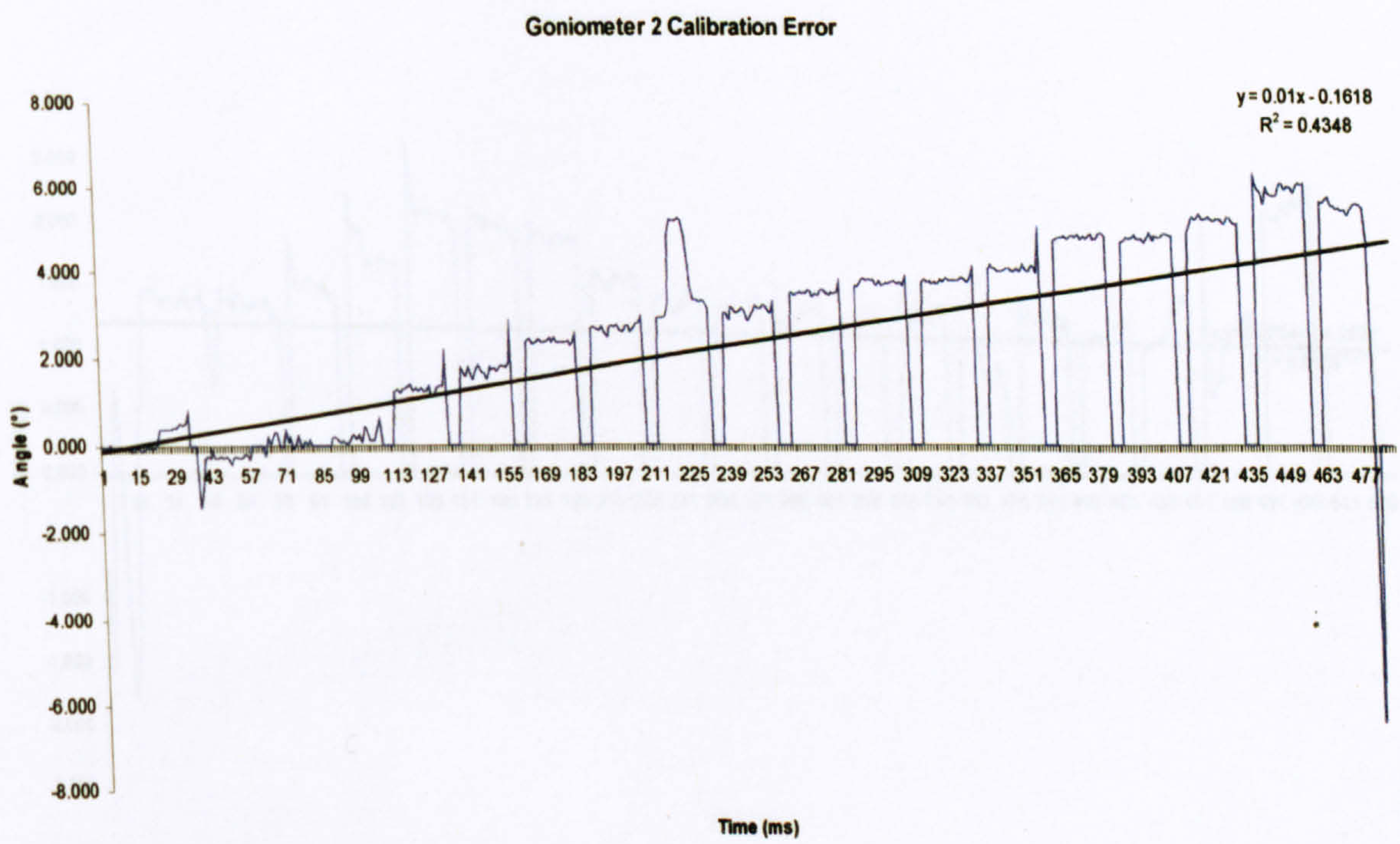


Figure C.12. Error identified in X-plane negative measure accuracy assessment of goniometer 2.



Goniometer 2 Calibration Y-plane - Positive

Figure C.13. Y-plane positive measure accuracy assessment of goniometer 2.

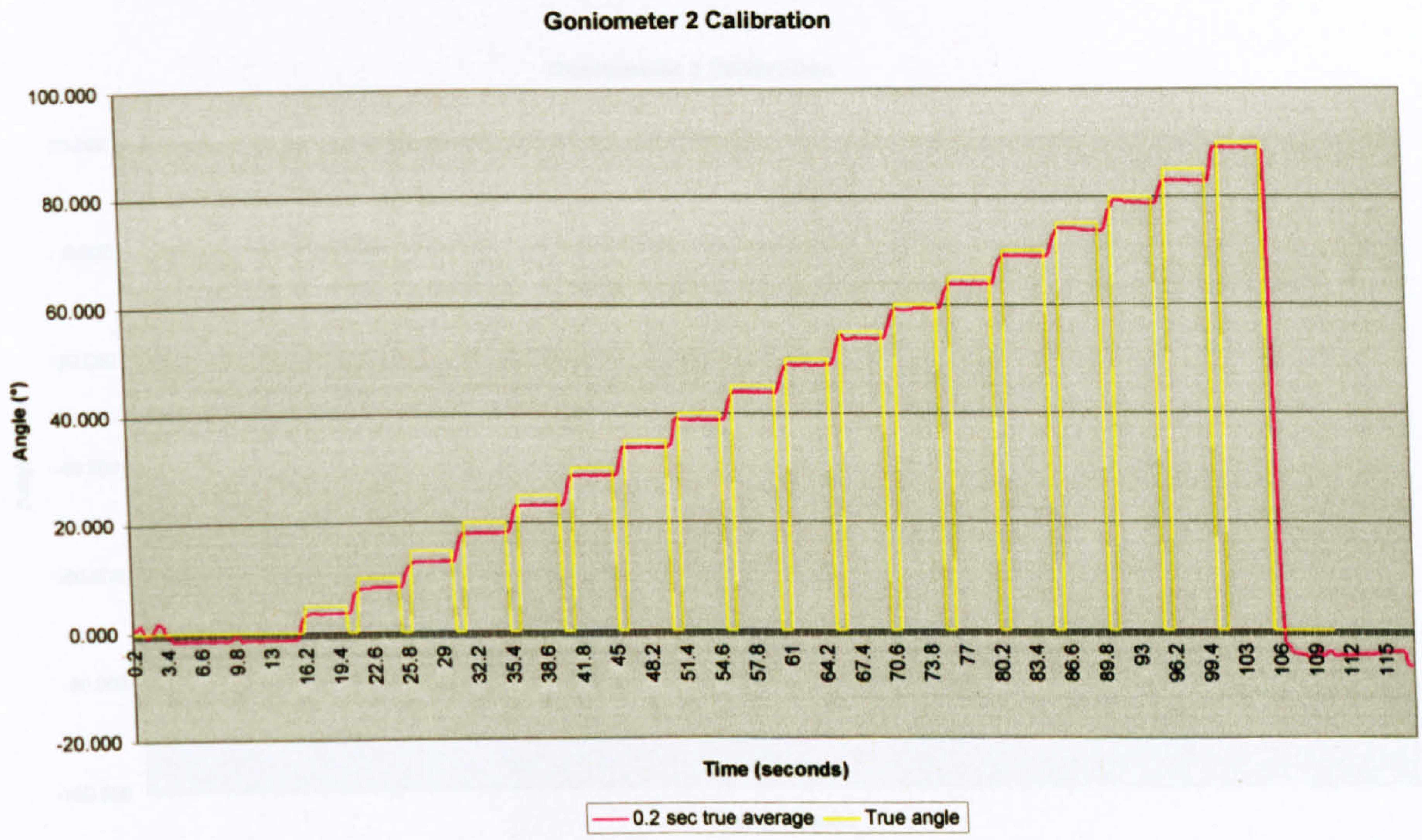
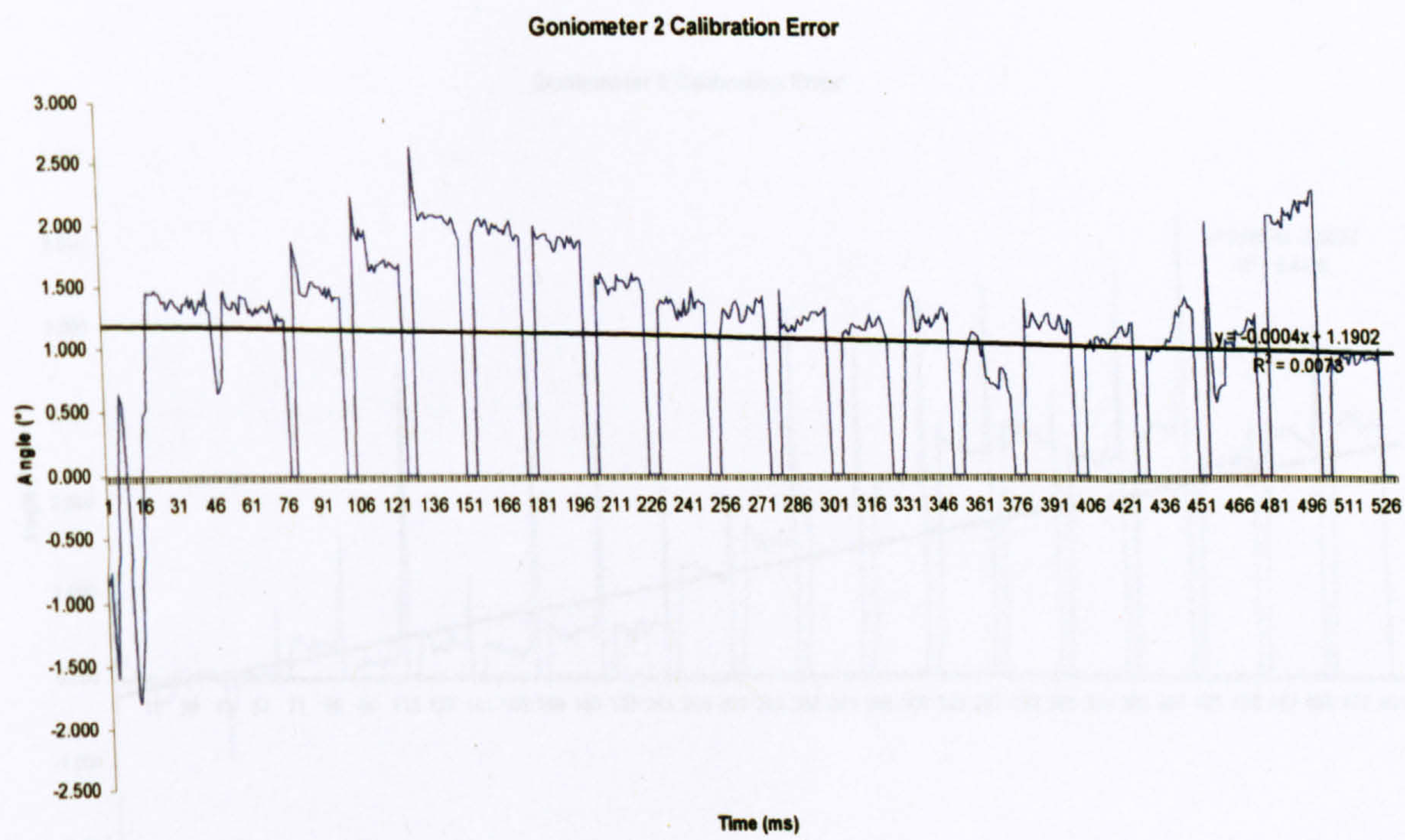


Figure C.14. Error identified in Y-plane positive measure accuracy assessment of goniometer 2.



Goniometer 2 Calibration Y-plane - Negative

Figure C.15. Y-plane negative measure accuracy assessment of goniometer 2.

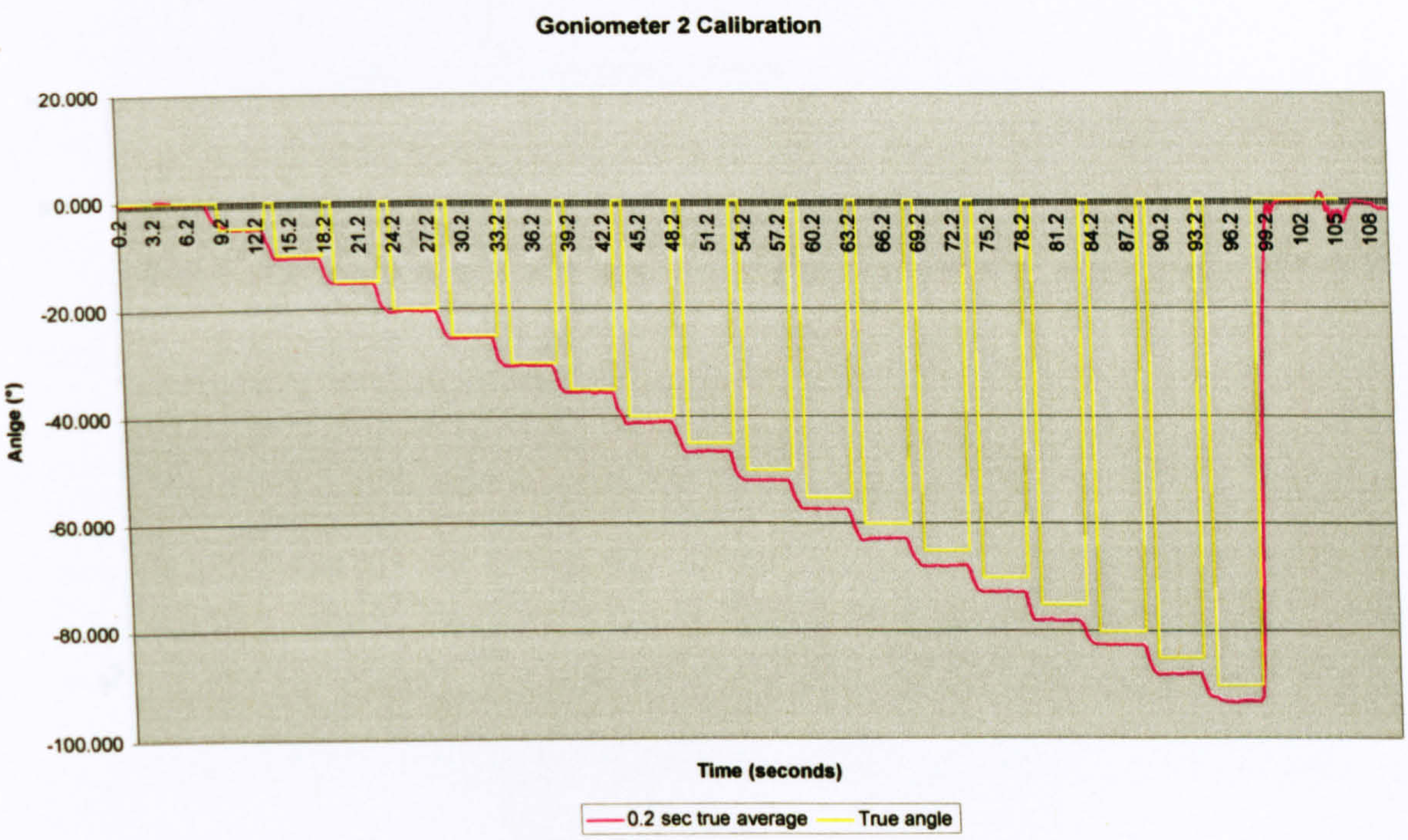
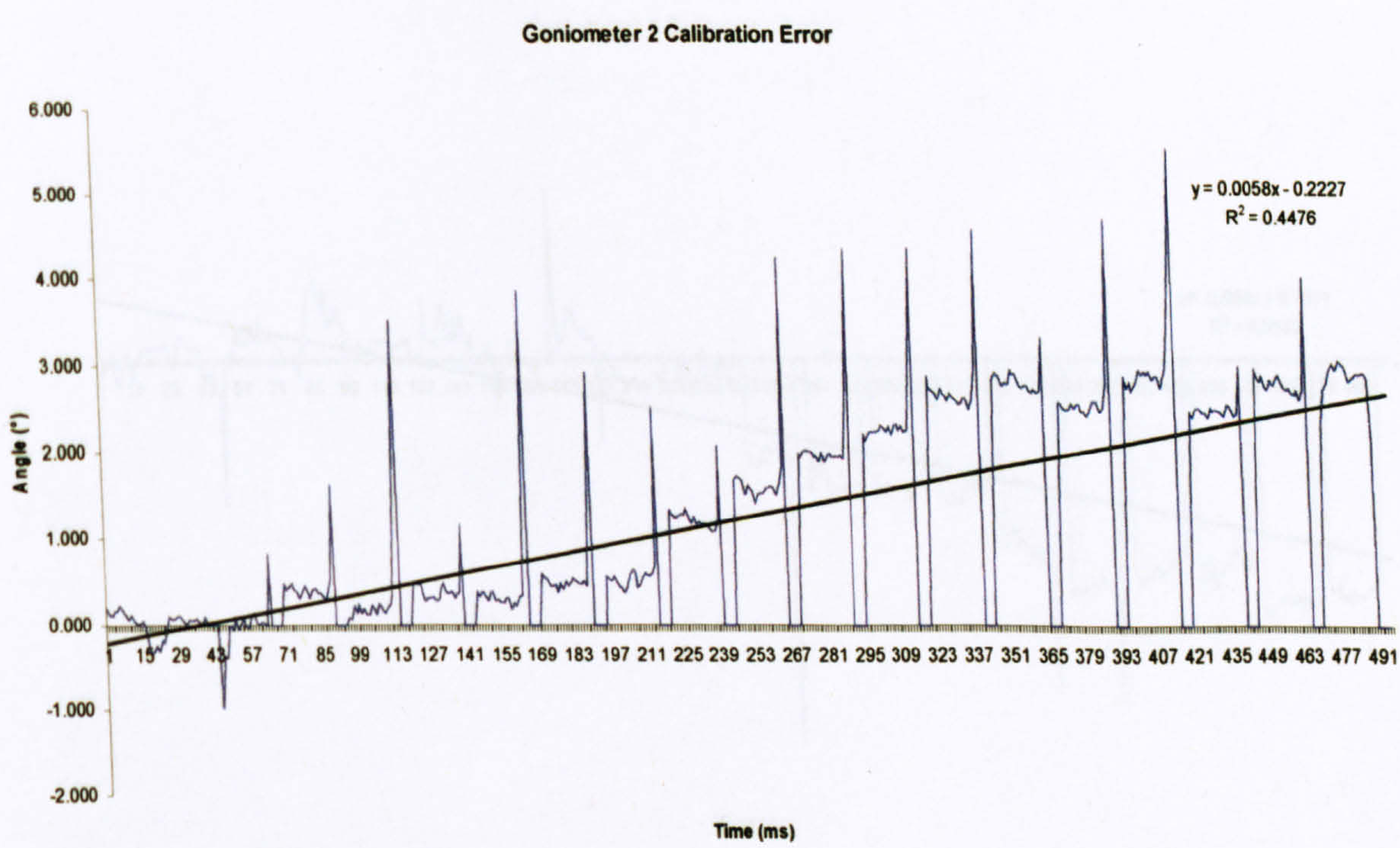


Figure C.16. Error identified in Y-plane negative measure accuracy assessment of goniometer 2.



Goniometer 3 X-plane Positive

Figure C.17. X-plane positive measure accuracy assessment of goniometer 3.

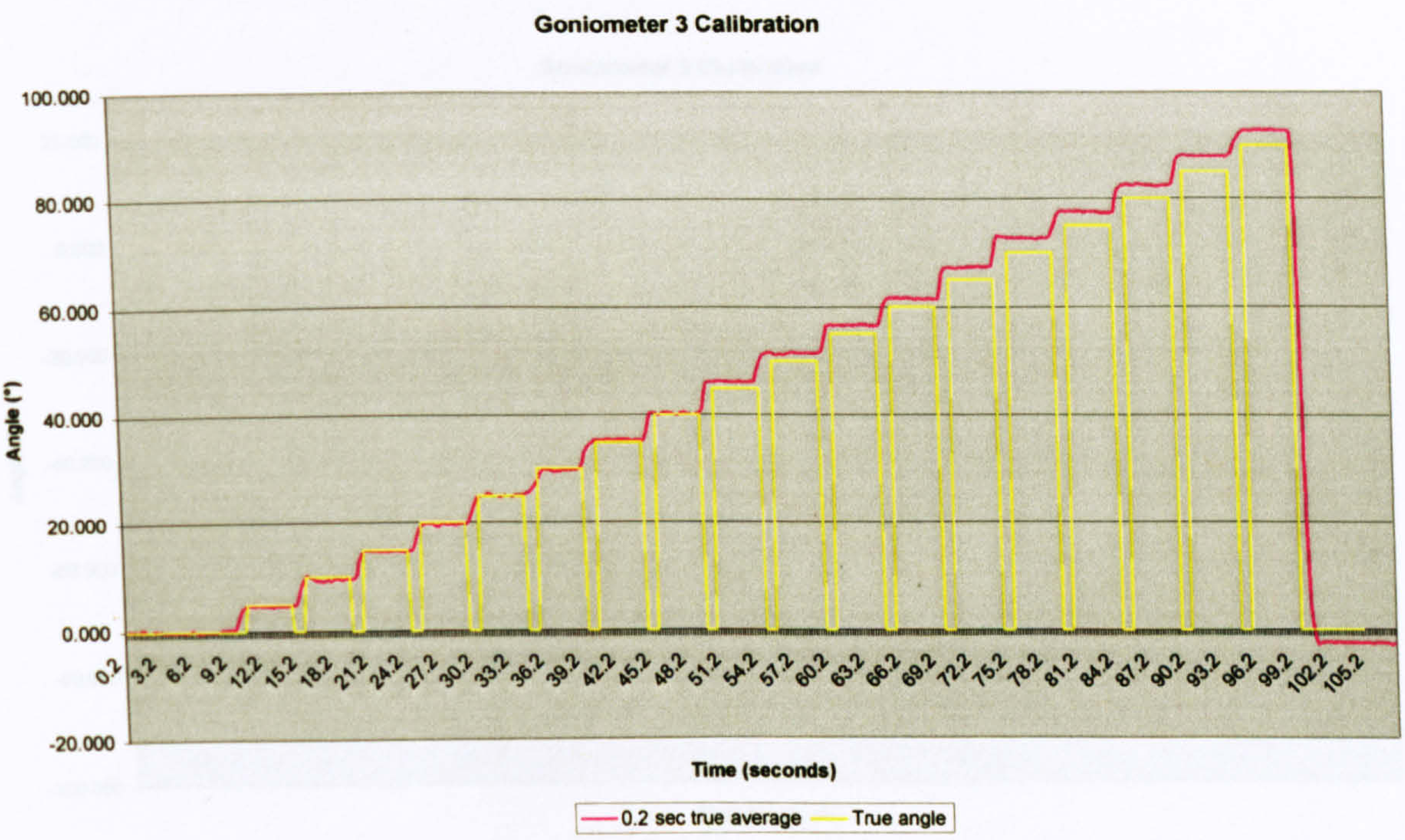
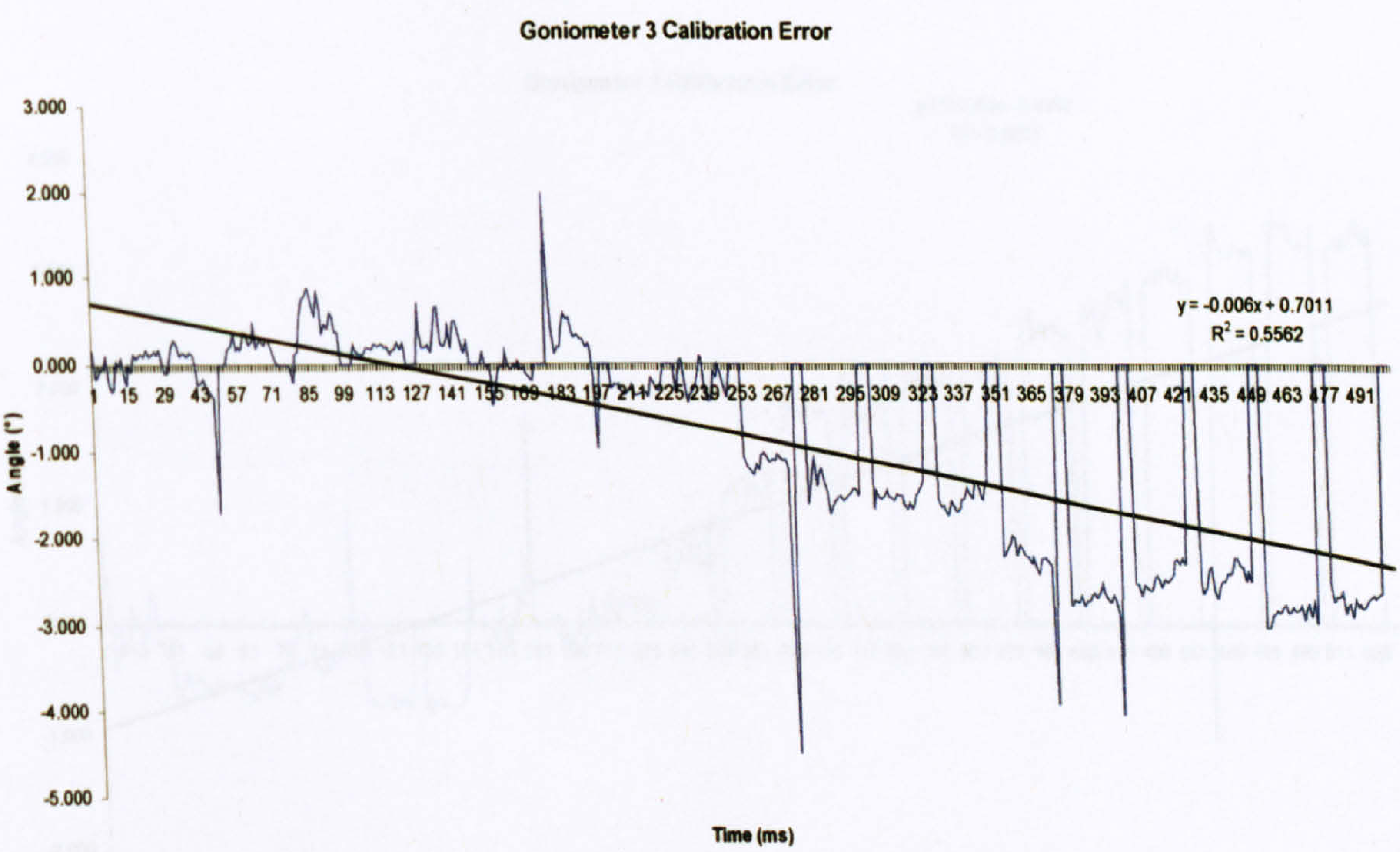


Figure C.18. Error identified in X-plane positive measure accuracy assessment of goniometer 3.



Goniometer 3 X-plane Negative

Figure C.19. X-plane negative measure accuracy assessment of goniometer 3.

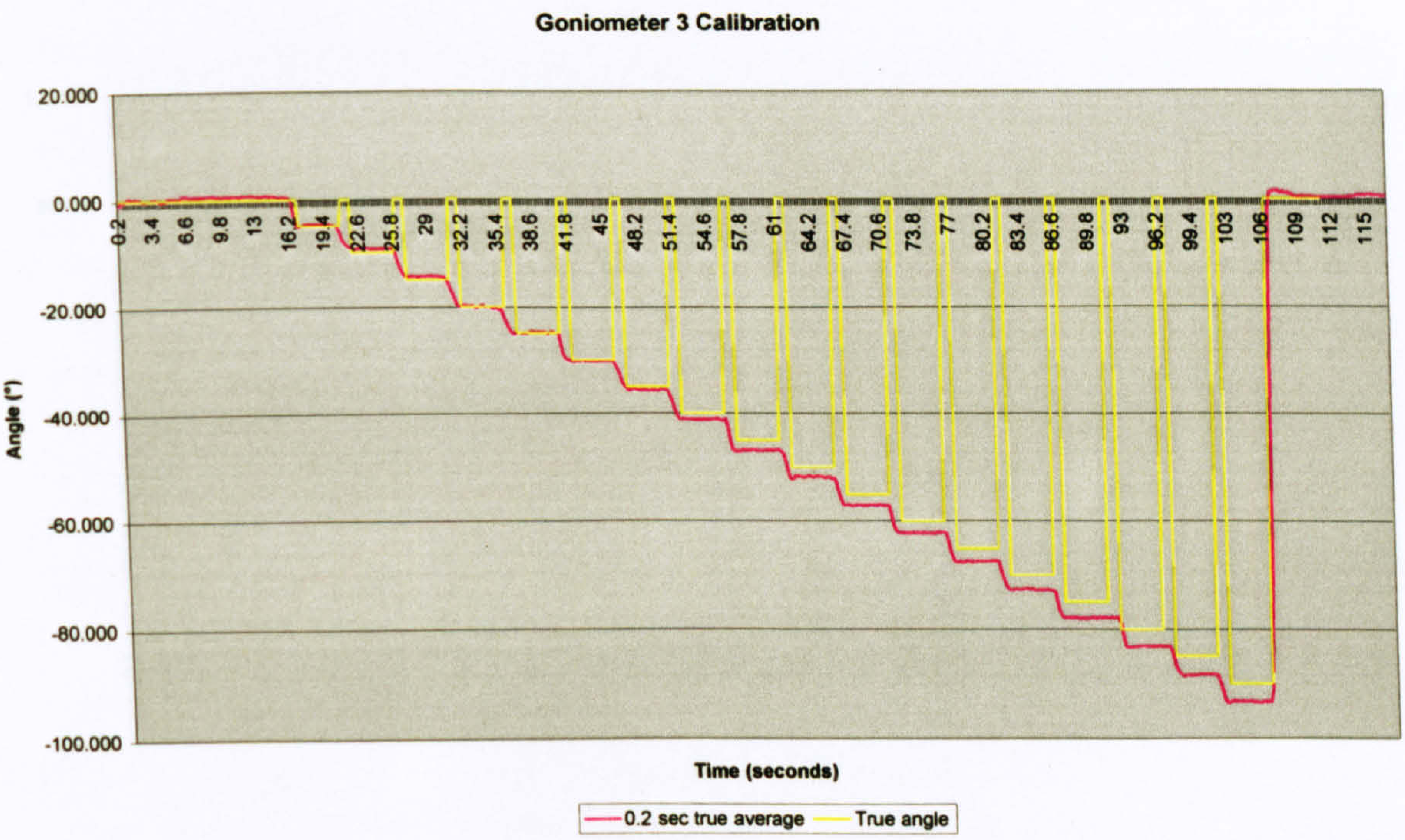
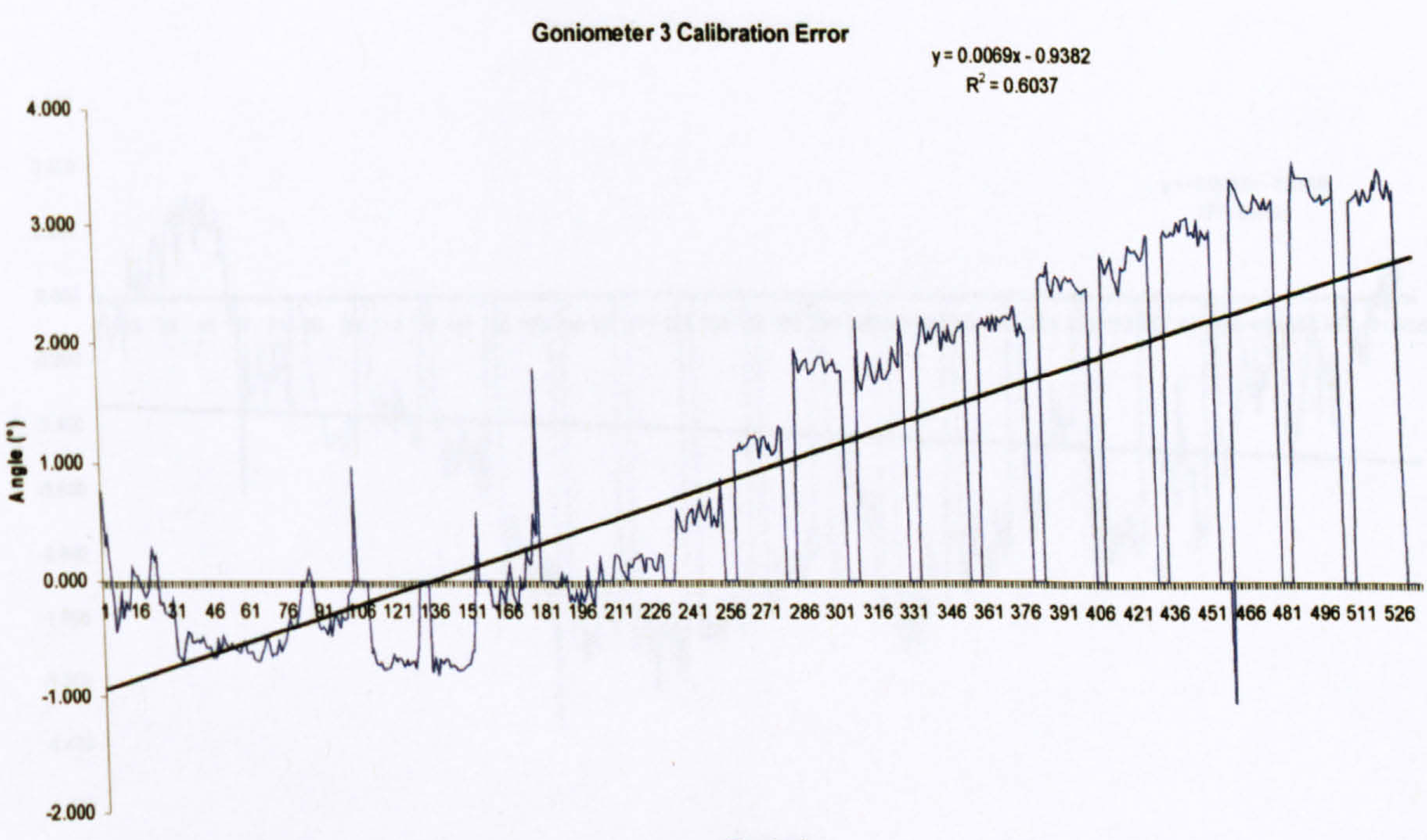


Figure C.20. Error identified in X-plane negative measure accuracy assessment of goniometer 3.



Goniometer 3 Calibration Y-plane - Positive

Figure C.21. Y-plane positive measure accuracy assessment of goniometer 3.

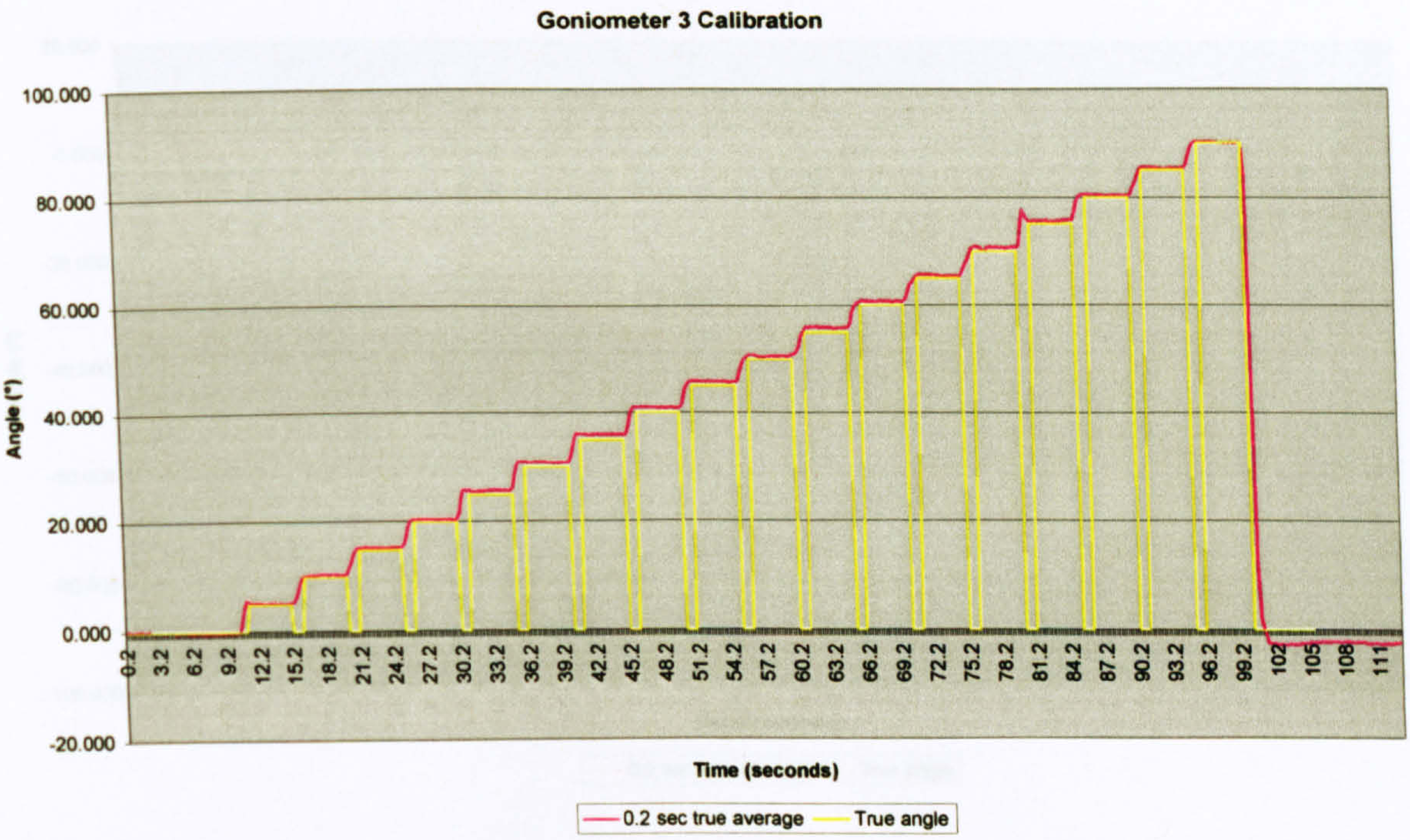
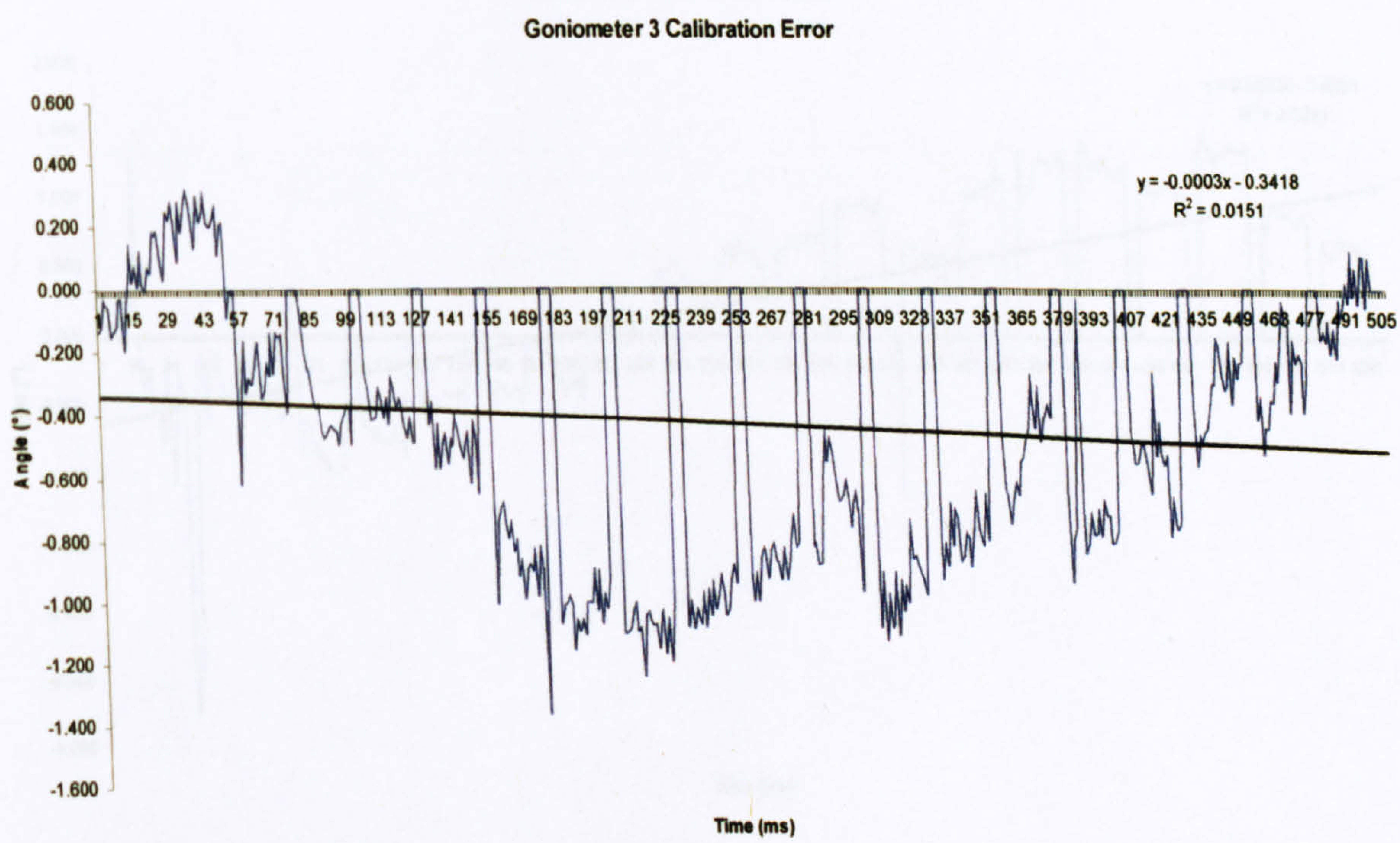


Figure C.22. Error identified in Y-plane positive measure accuracy assessment of goniometer 3.



Goniometer 3 Calibration Y-plane - Negative

Figure C.23. Y-plane negative measure accuracy assessment of goniometer 3.

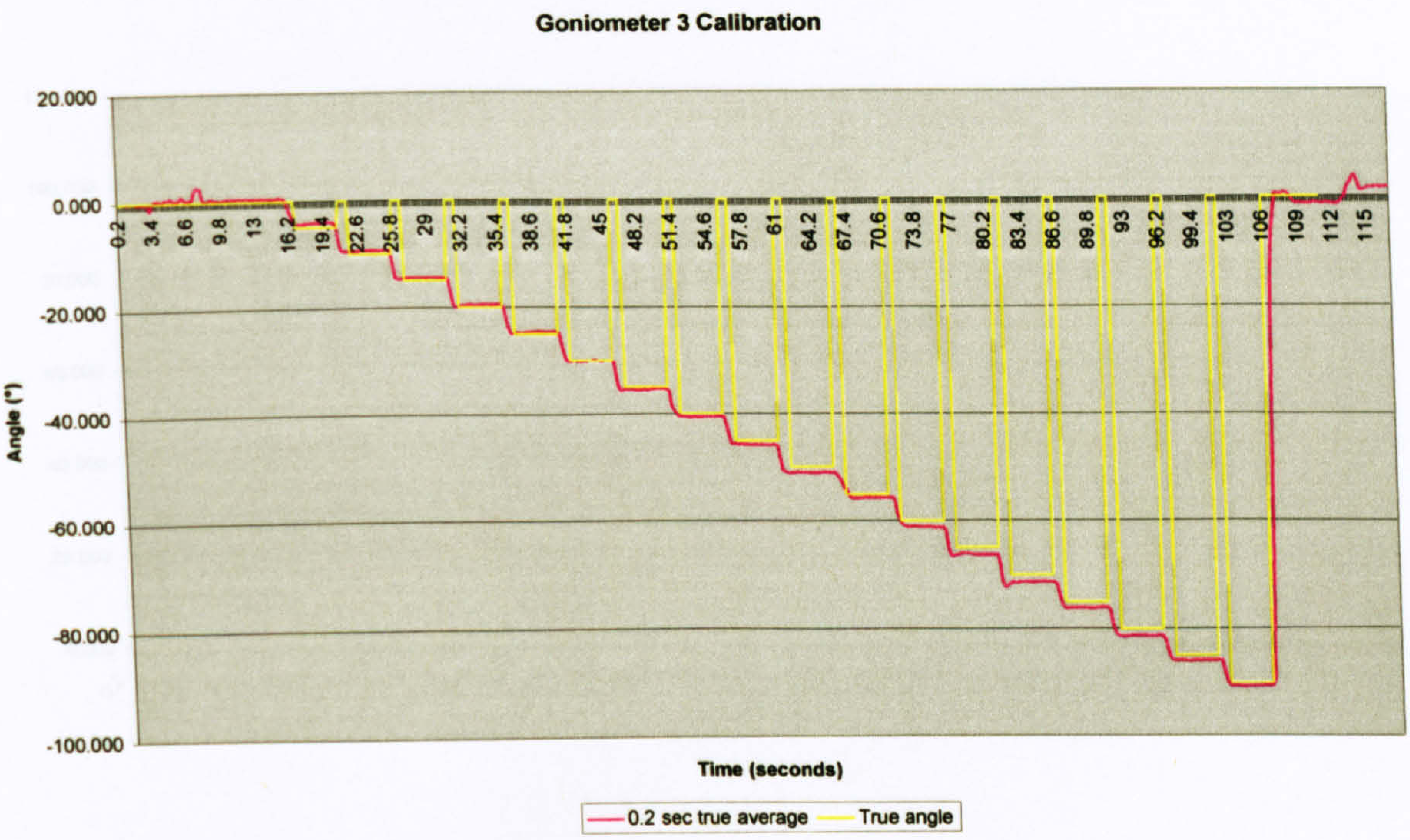
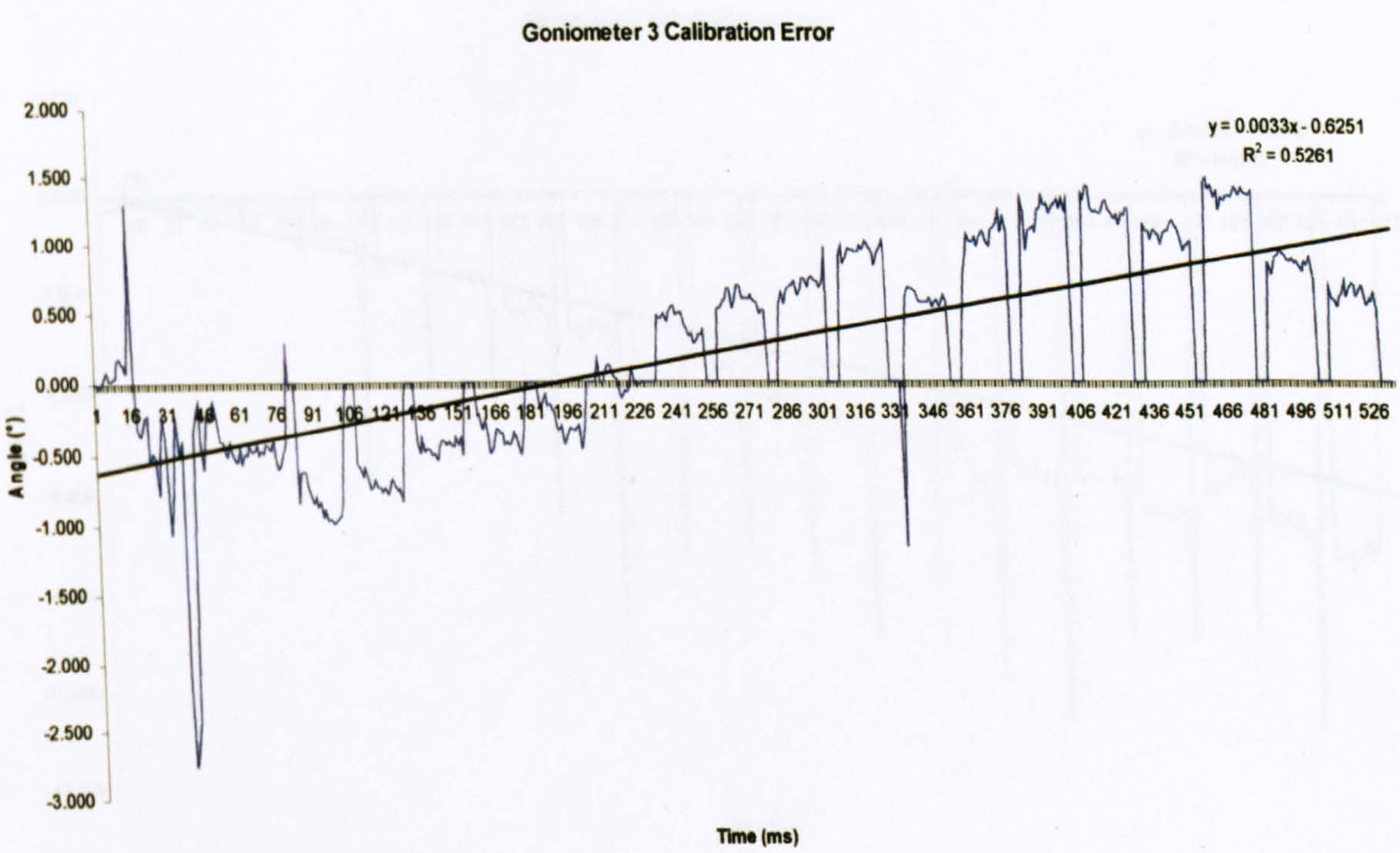


Figure C.24. Error identified in Y-plane negative measure accuracy assessment of goniometer 3.



Goniometer 4 X-plane - Positive

Figure C.25. X-plane positive measure accuracy assessment of goniometer 4.

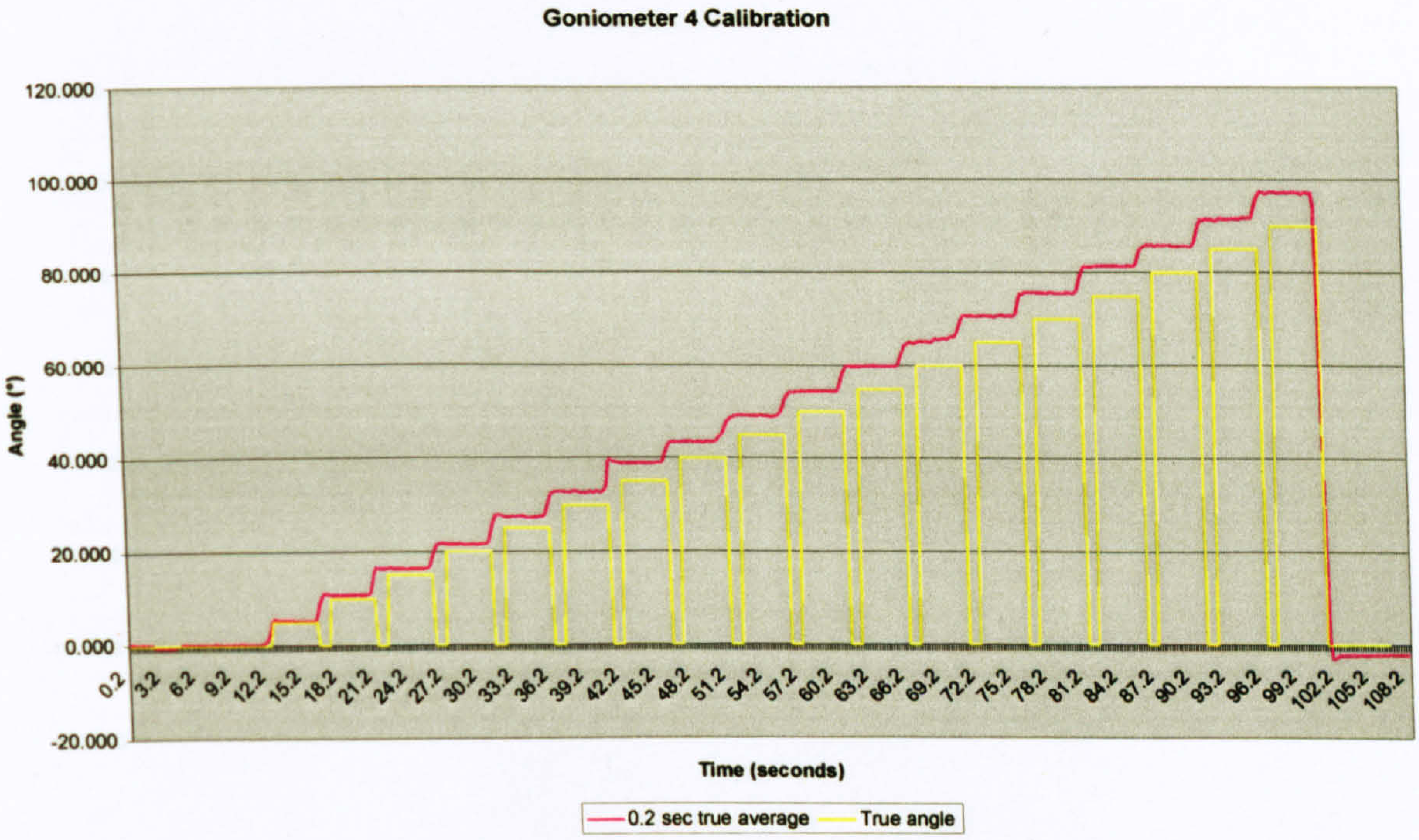
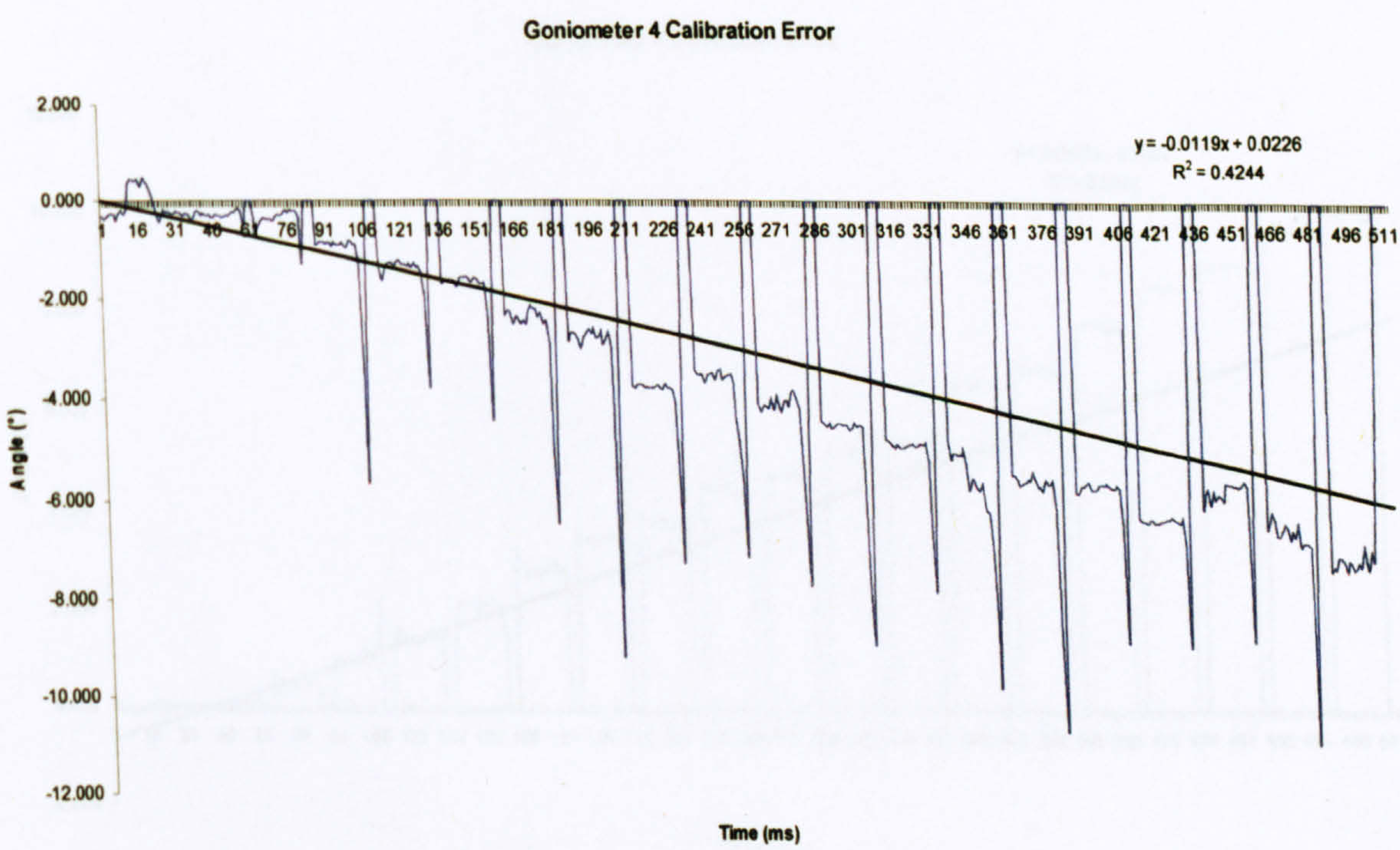


Figure C.26. Error identified in X-plane positive measure accuracy assessment of goniometer 4.



Goniometer 4 X-plane – Negative

Figure C.27. X-plane negative measure accuracy assessment of goniometer 4.

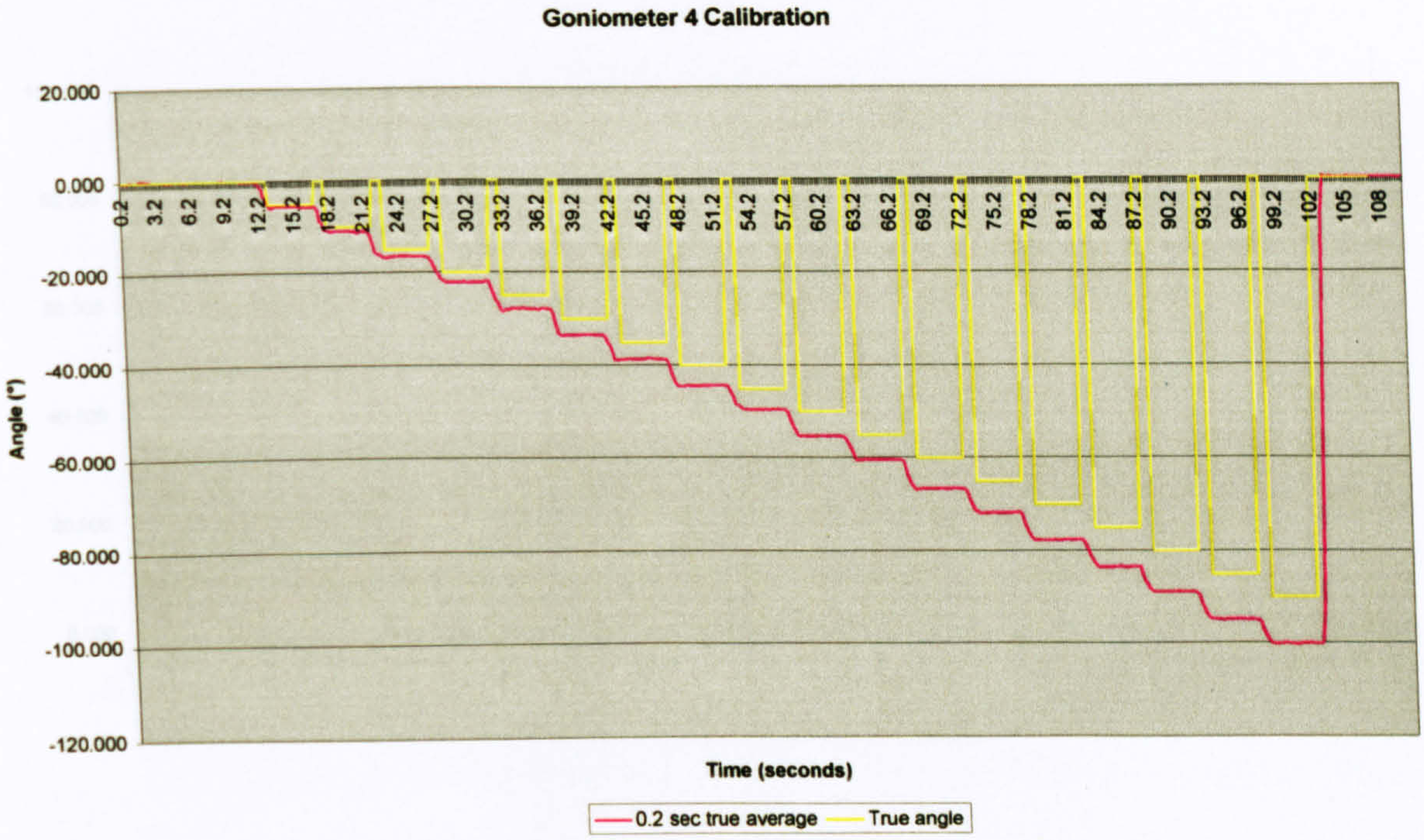
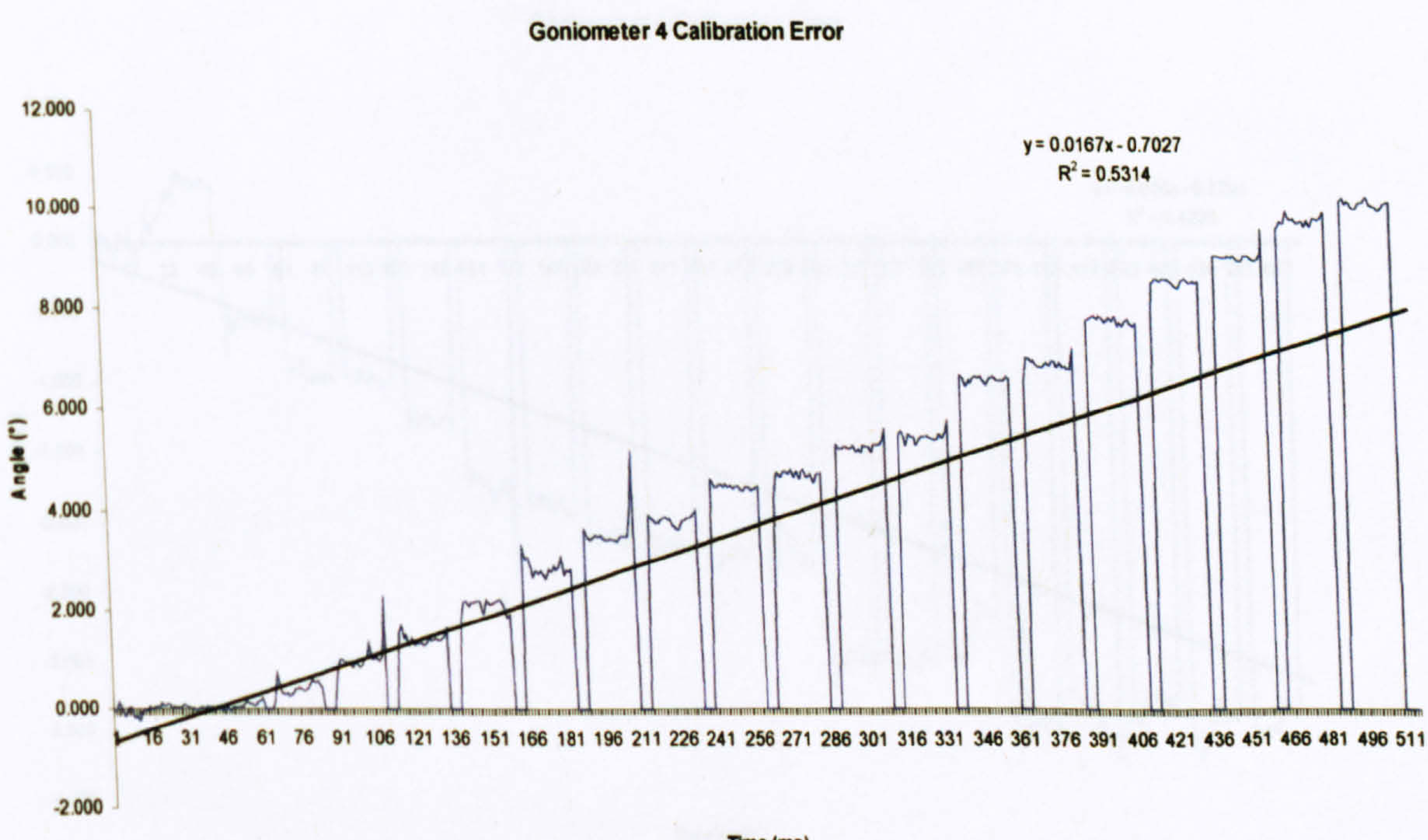


Figure C.28. Error identified in X-plane negative measure accuracy assessment of goniometer 4.



Goniometer 4 Calibration Y-plane - Positive

Figure C.29. X-plane positive measure accuracy assessment of goniometer 4.

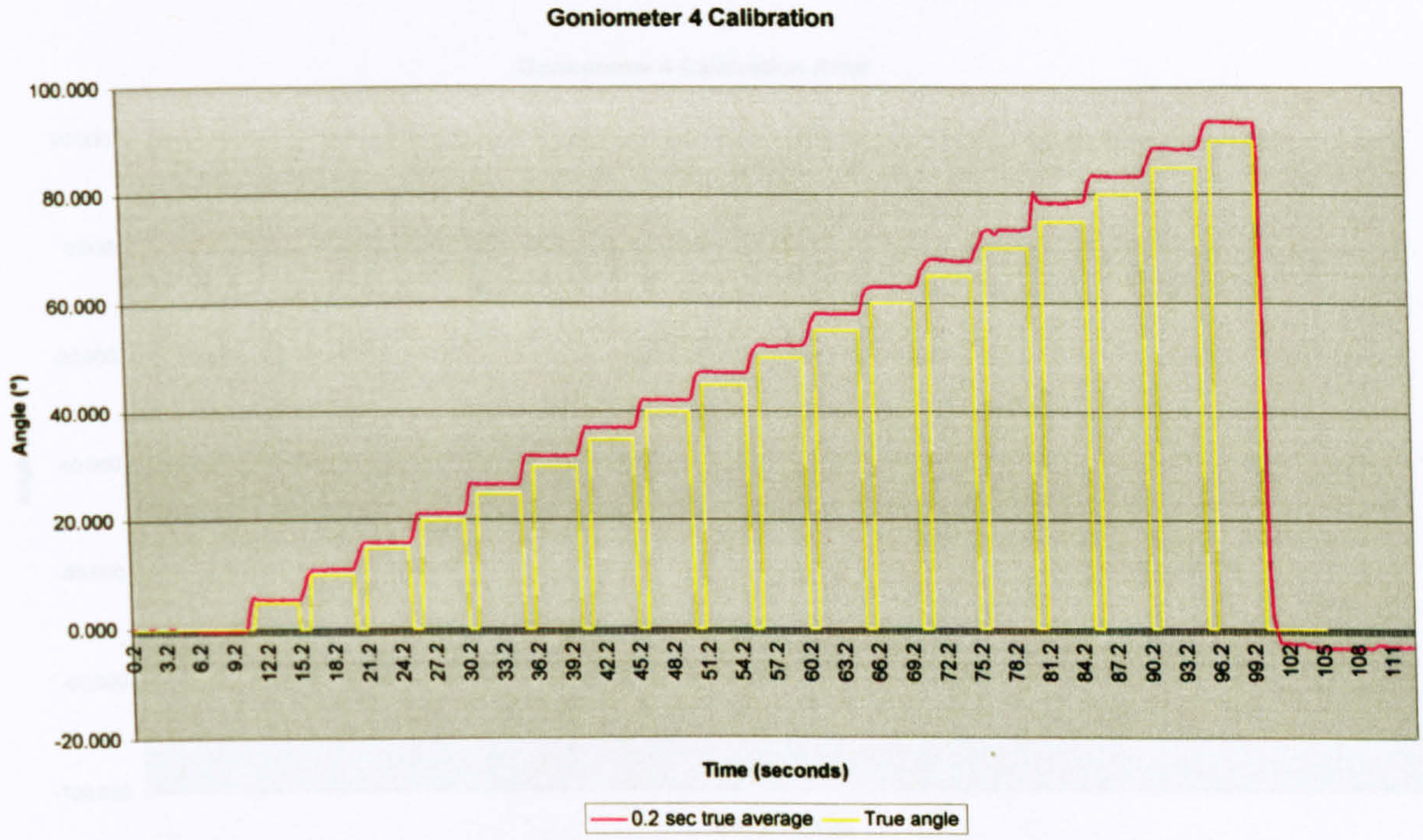
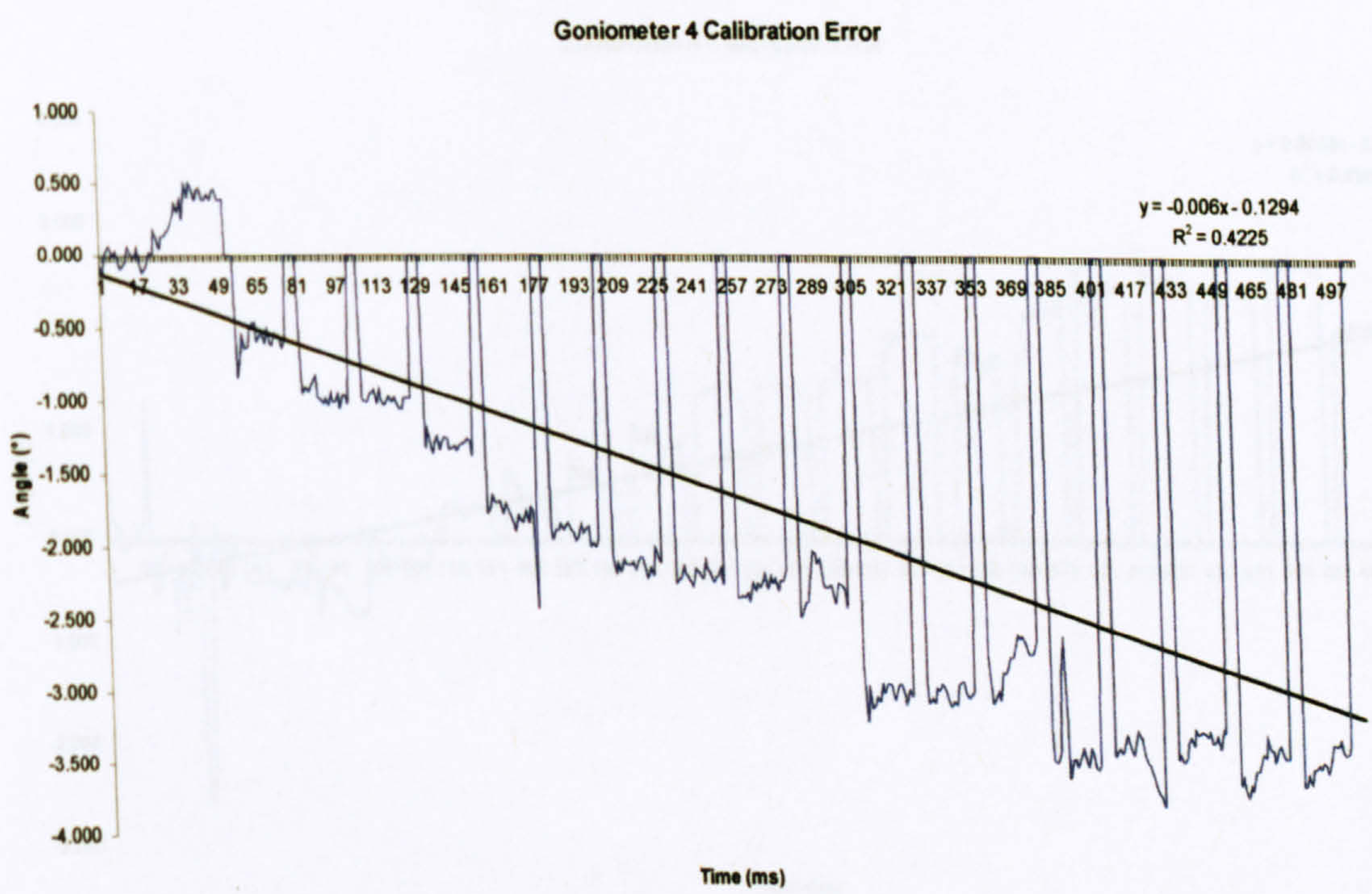


Figure C.30. Error identified in Y-plane positive measure accuracy assessment of goniometer 4.



Goniometer 4 Calibration Y-plane - Negative

Figure C.31. Y-plane negative measure accuracy assessment of goniometer 4.

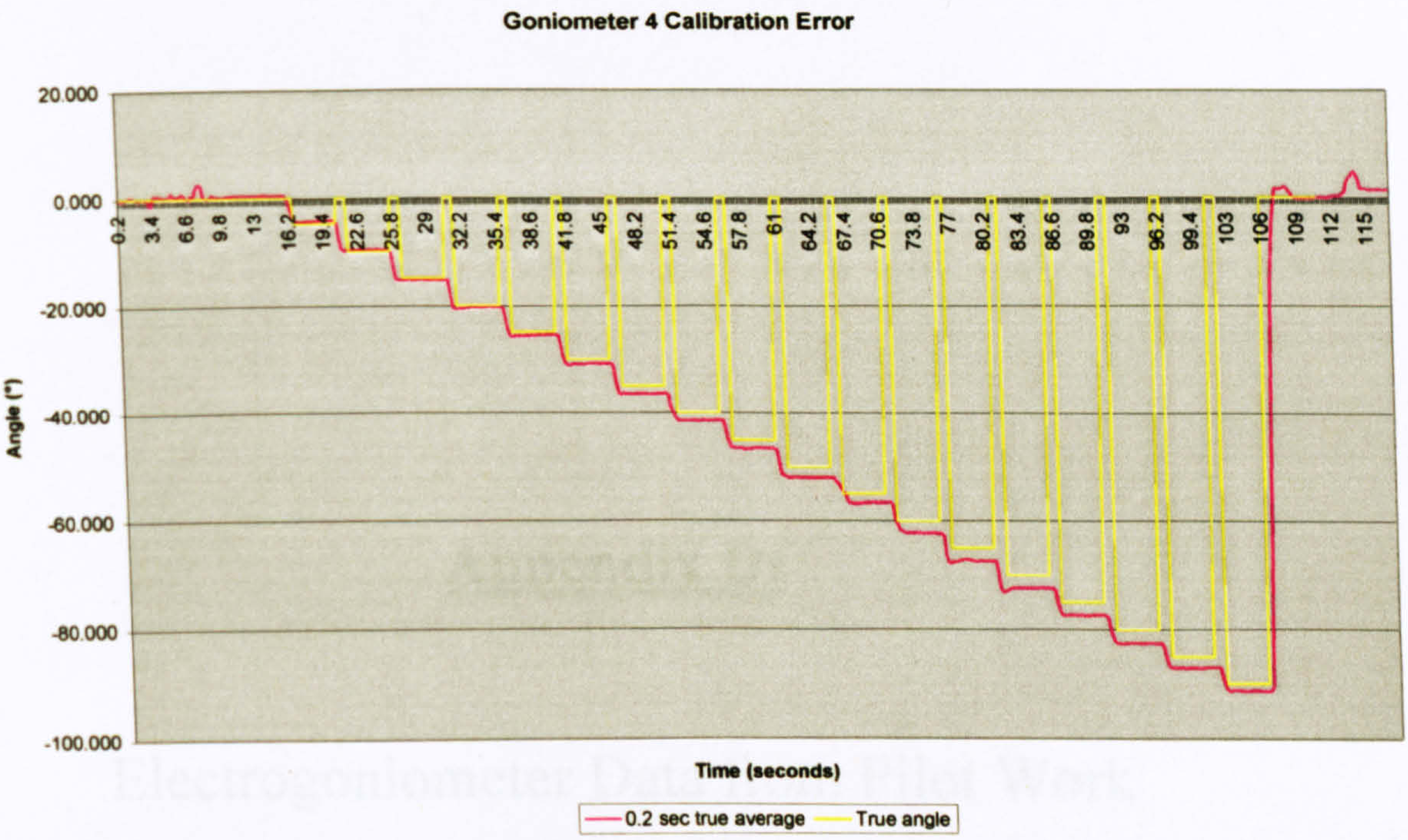
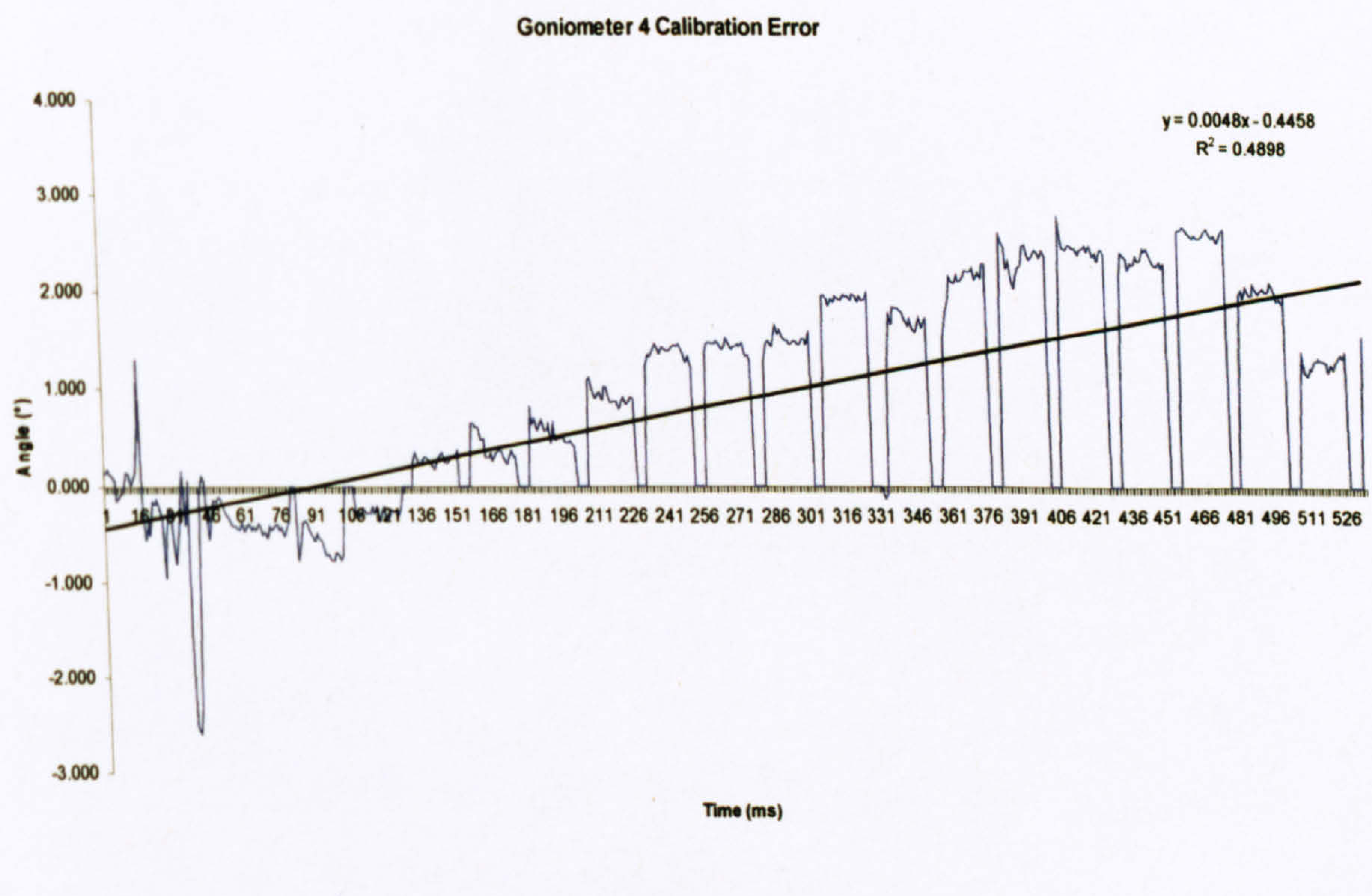


Figure C.32. Error identified in Y-plane negative measure accuracy assessment of goniometer 4.



Appendix D:

Electrogoniometer Data from Pilot Work

Subject 1

Figure D.1. Angular motion of the knee and trunk for Subject 1 Trial 1

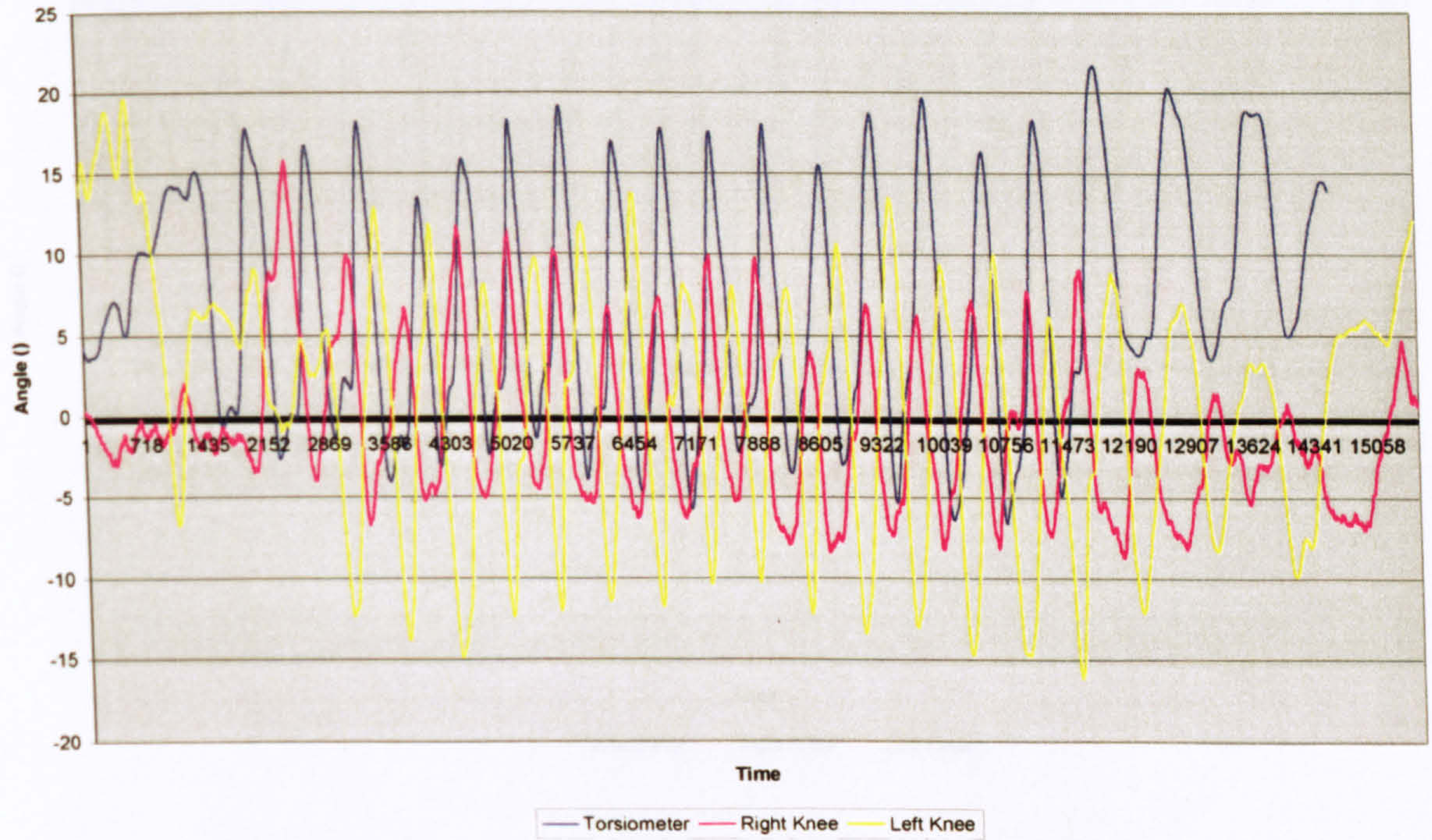


Figure D.2. Angular motion of the knee and trunk for Subject 1 Trial 2

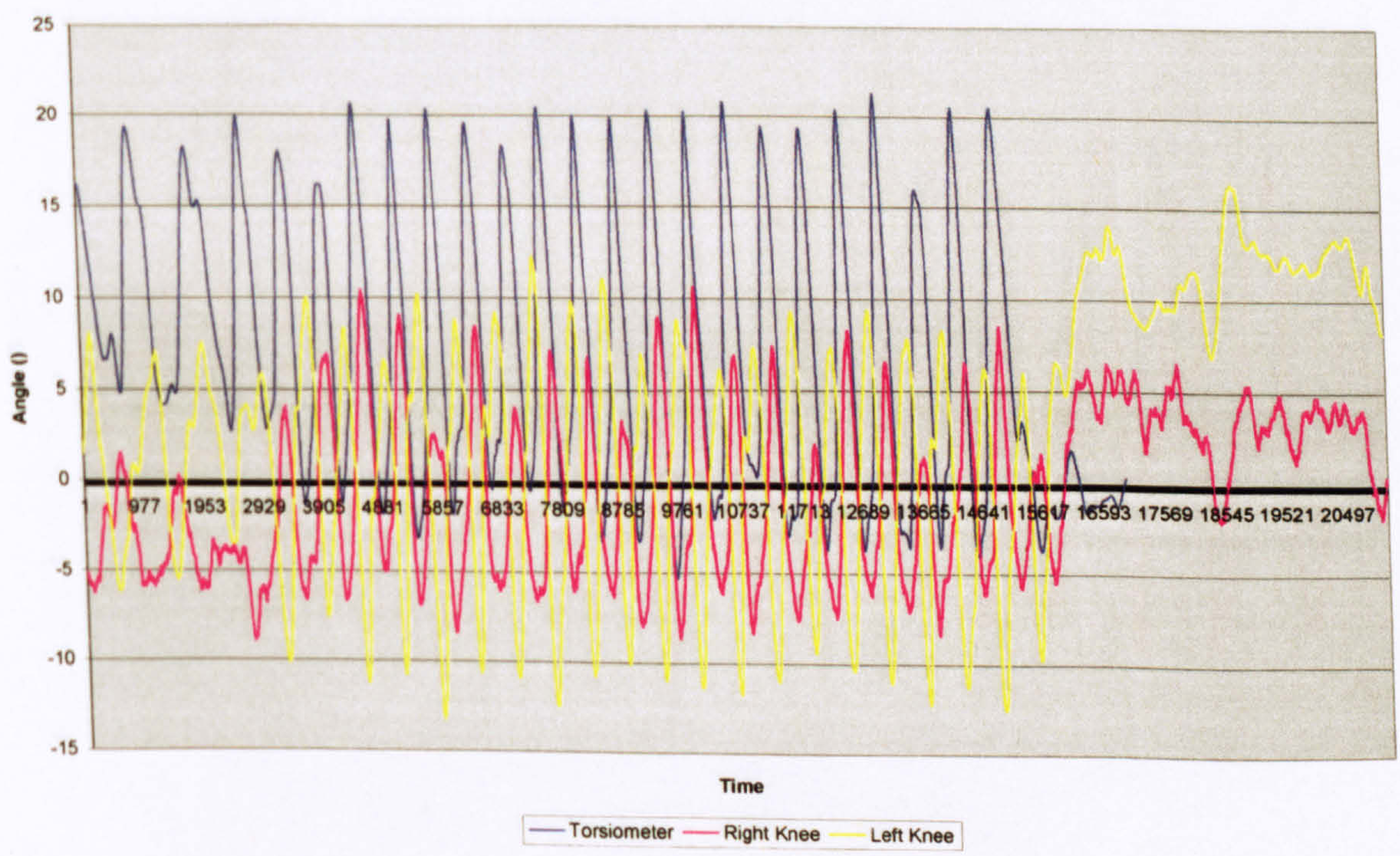
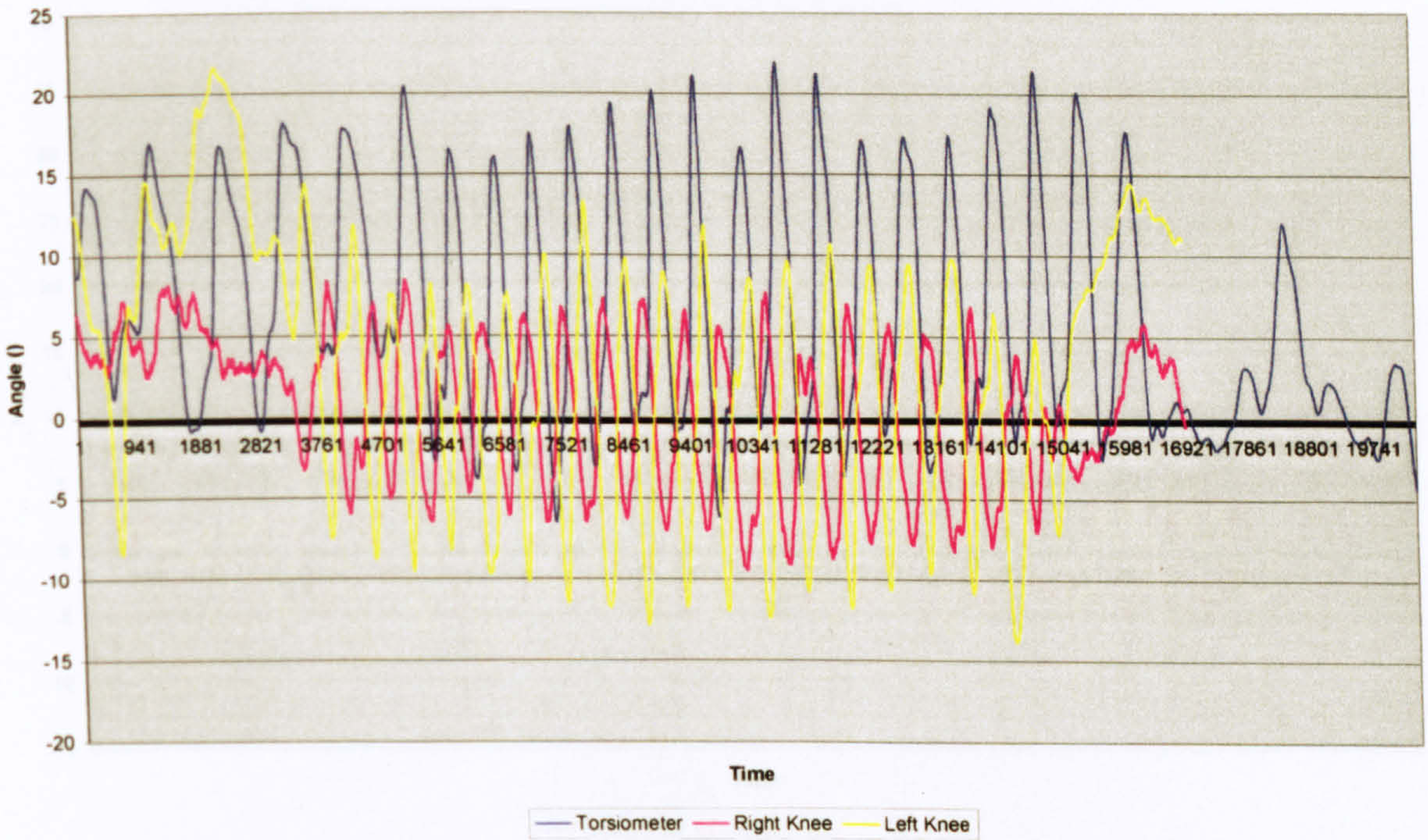


Figure D.3. Angular motion of the knee and trunk for Subject 1 Trial 3



Subject 2

Figure D.4. Angular motion of the knee and trunk for Subject 2 Trial 1

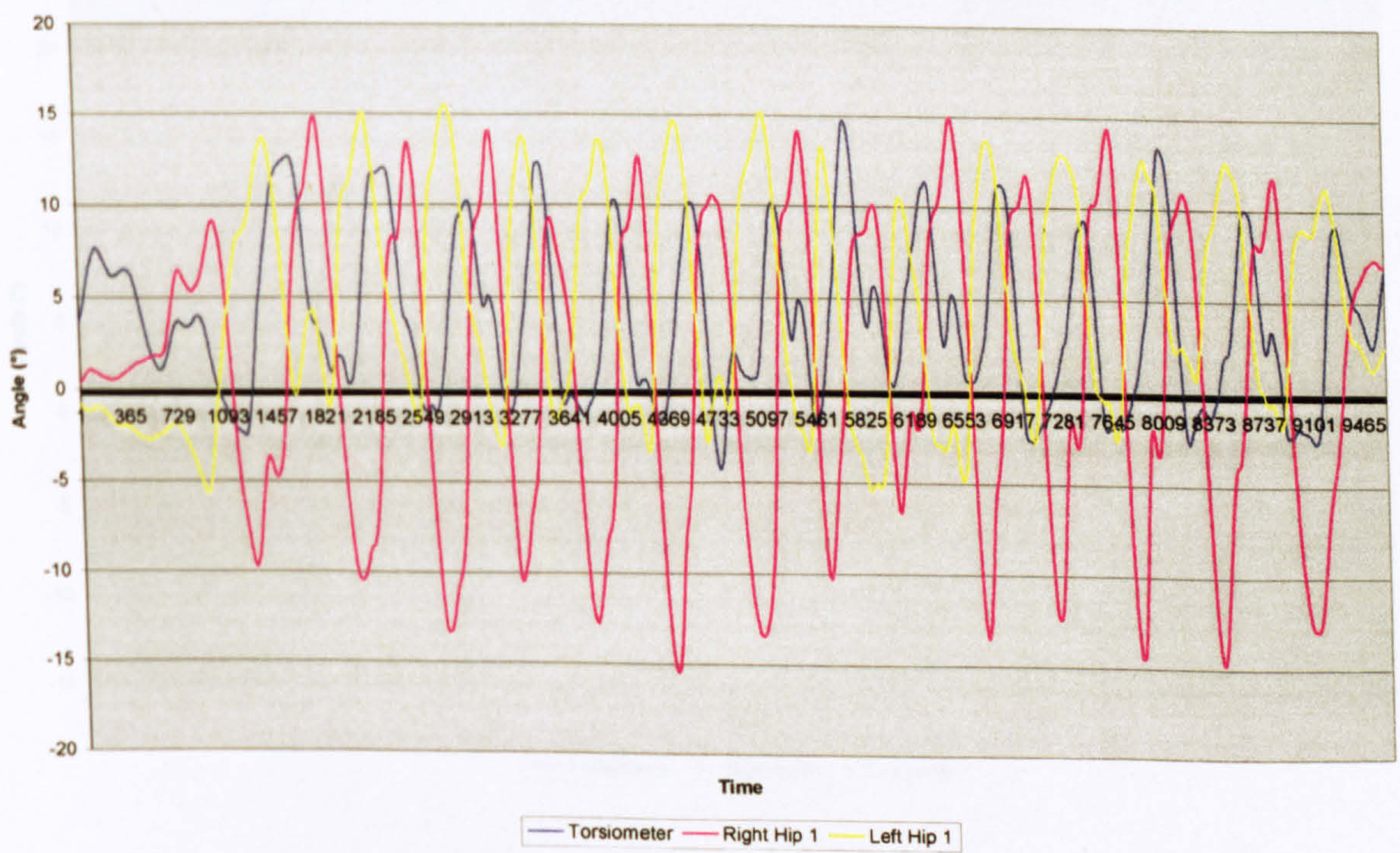


Figure D.5. Angular motion of the knee and trunk for Subject 2 Trial 2

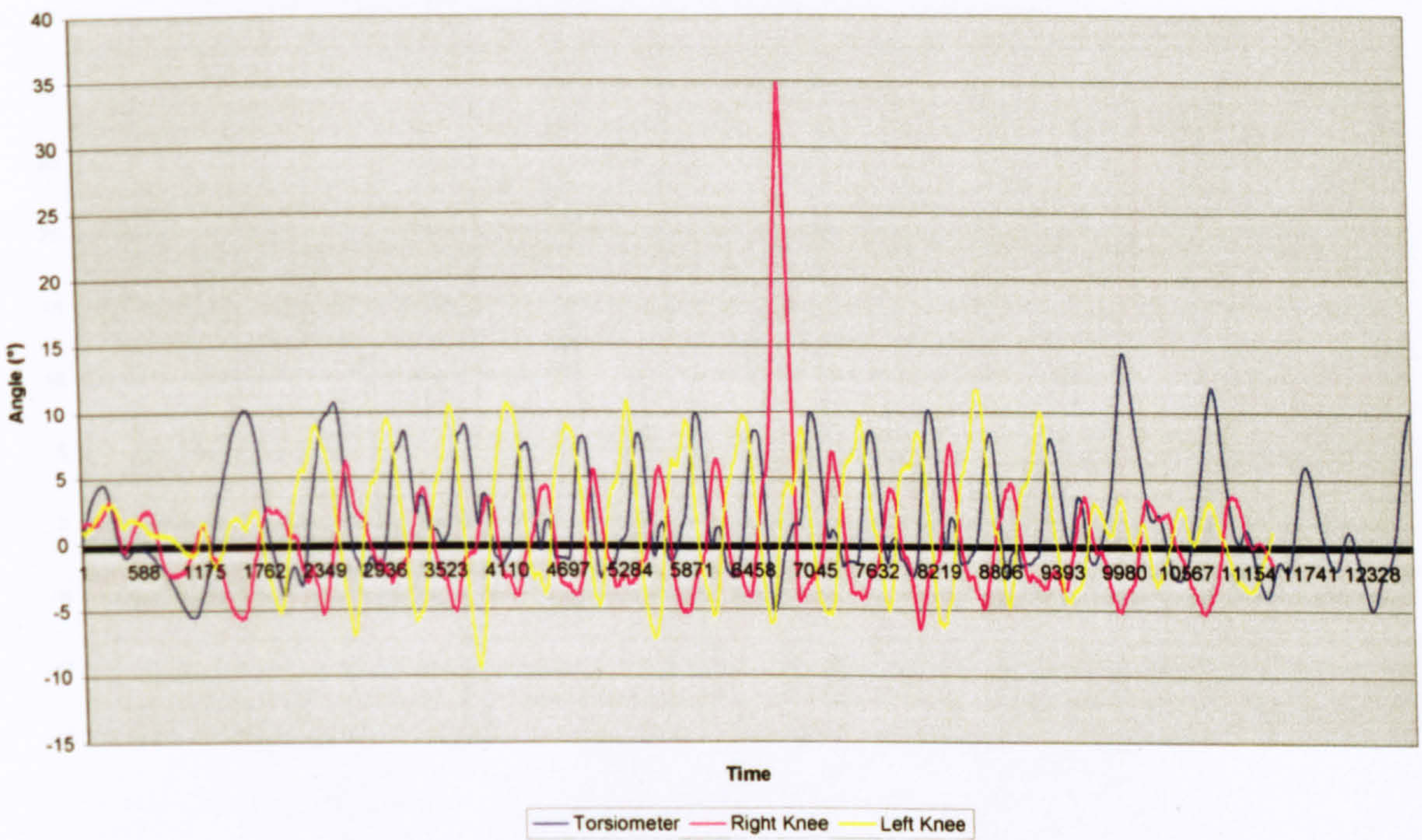


Figure D.6. Angular motion of the knee and trunk for Subject 2 Trial 3

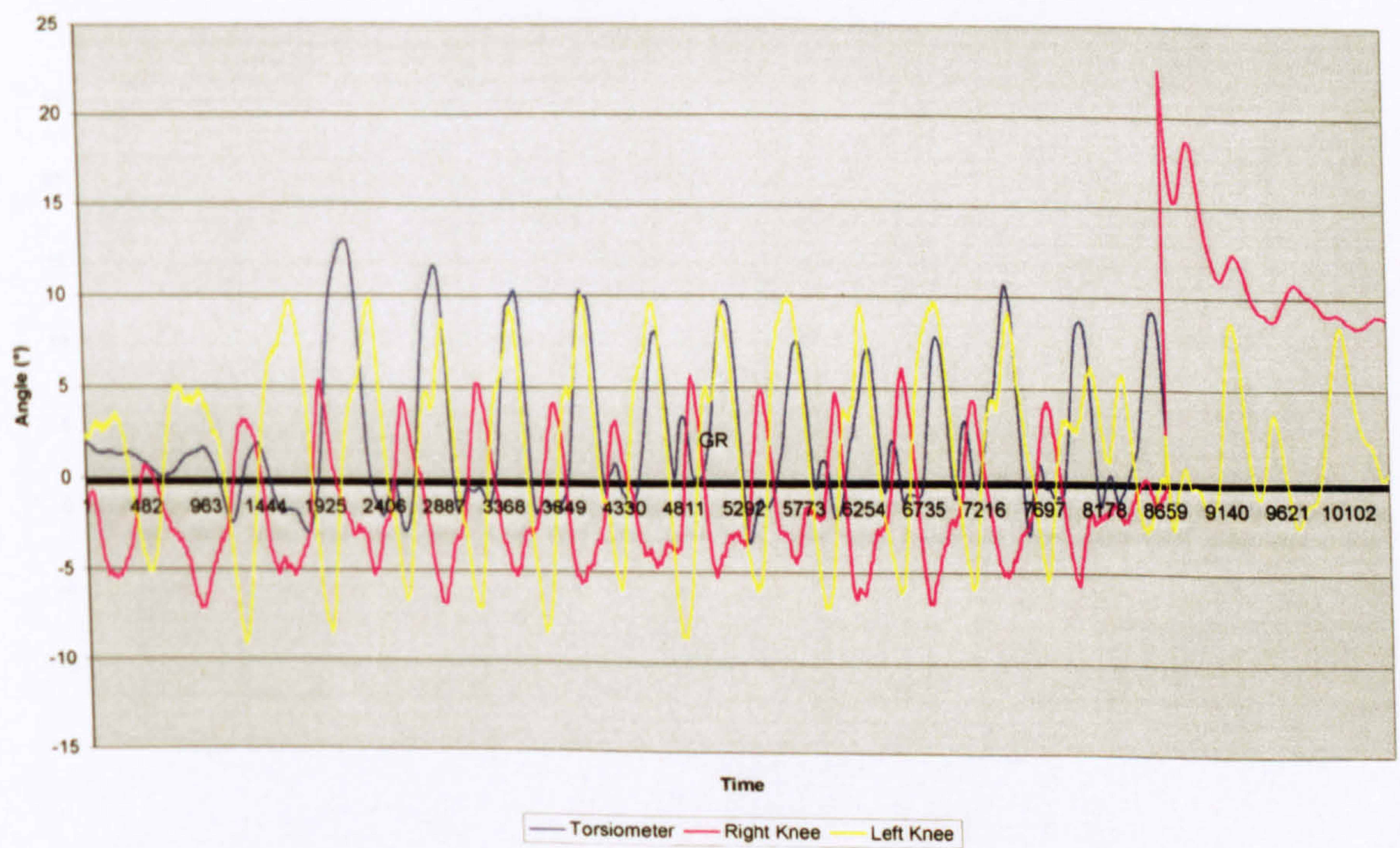


Figure D.7. Angular motion of the knee and trunk for Subject 2 Trial 4

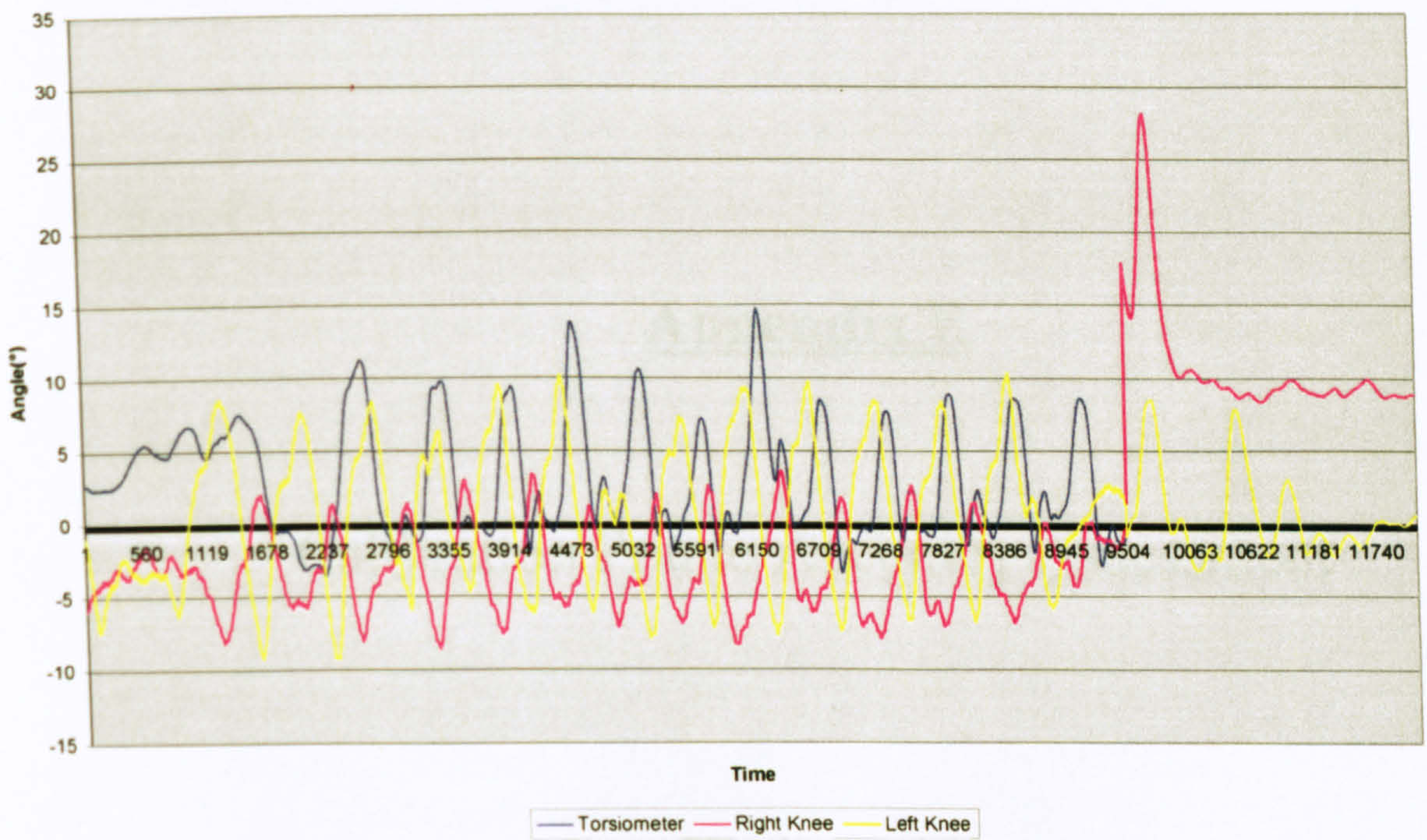
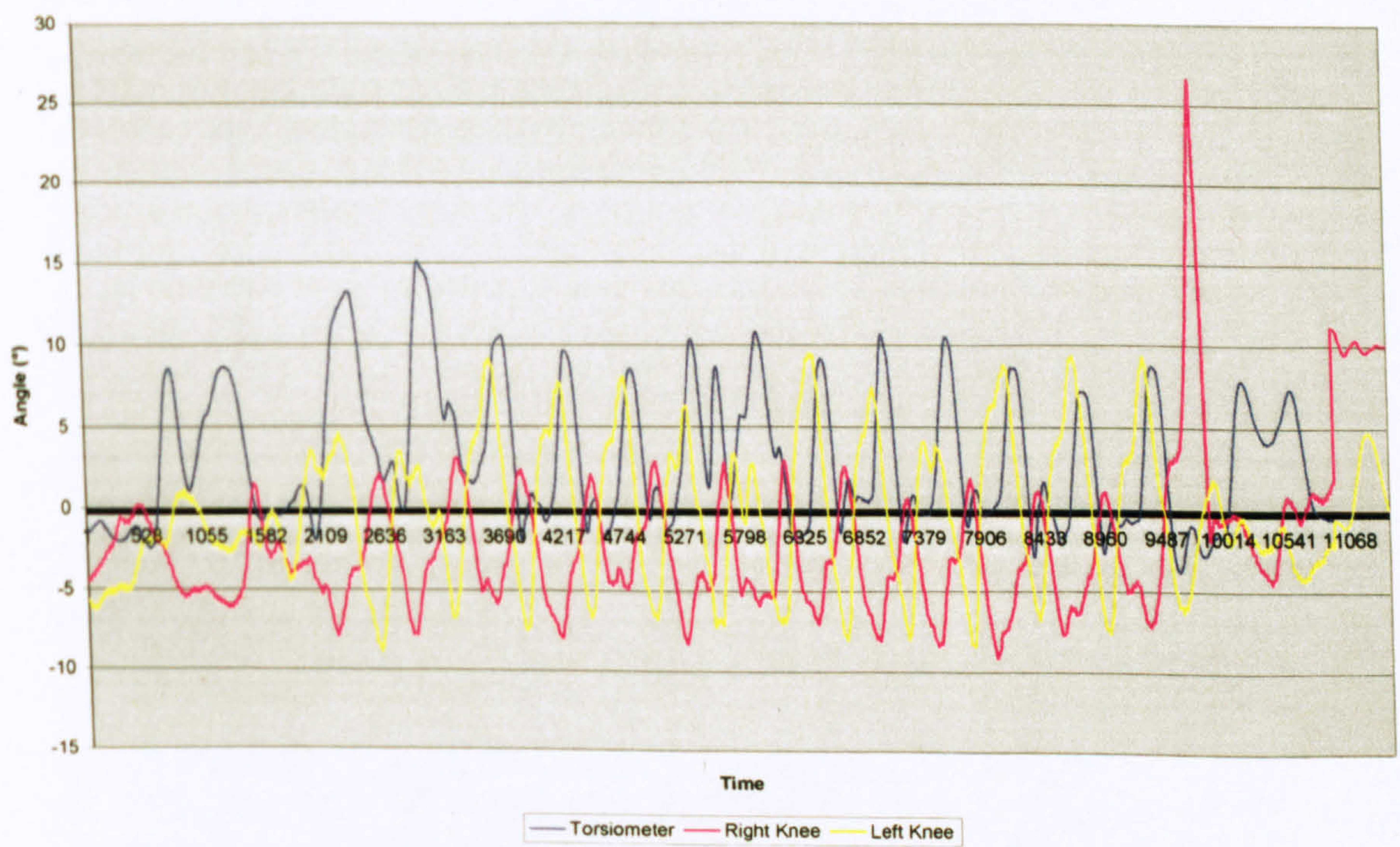


Figure D.8. Angular motion of the knee and trunk for Subject 2 Trial 5



Appendix E

Calibration Frame Accuracy Assessment

Trial	t1			t2			t3			t4			t5		
	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1.000	2.490	2.569	0.602	2.481	2.804	1.267	2.593	2.684	0.598	5.630	5.913	1.832	4.992	5.584	2.603
2.000	2.493	2.569	0.605	2.482	2.806	1.272	2.592	2.682	0.595	5.634	5.913	1.830	4.994	5.588	2.601
3.000	2.495	2.569	0.607	2.483	2.808	1.276	2.592	2.680	0.594	5.638	5.913	1.829	4.996	5.590	2.598
4.000	2.495	2.568	0.606	2.484	2.808	1.279	2.593	2.678	0.594	5.640	5.914	1.829	4.996	5.591	2.594
5.000	2.494	2.567	0.604	2.483	2.808	1.281	2.595	2.678	0.596	5.639	5.915	1.829	4.995	5.591	2.592
6.000	2.493	2.567	0.604	2.482	2.807	1.280	2.597	2.677	0.597	5.635	5.916	1.830	4.994	5.590	2.591
7.000	2.494	2.568	0.604	2.481	2.806	1.276	2.597	2.677	0.598	5.632	5.916	1.830	4.993	5.590	2.591
8.000	2.495	2.568	0.605	2.480	2.805	1.269	2.595	2.677	0.597	5.629	5.915	1.830	4.993	5.591	2.590
9.000	2.497	2.569	0.605	2.481	2.804	1.262	2.593	2.677	0.597	5.628	5.913	1.829	4.993	5.592	2.587
10.000	2.500	2.569	0.603	2.482	2.805	1.258	2.591	2.677	0.596	5.628	5.910	1.829	4.994	5.593	2.584
11.000	2.502	2.569	0.601	2.483	2.805	1.257	2.589	2.677	0.596	5.627	5.909	1.828	4.994	5.593	2.582
12.000	2.503	2.569	0.599	2.485	2.805	1.257	2.588	2.676	0.595	5.627	5.909	1.828	4.994	5.593	2.581
13.000	2.502	2.569	0.599	2.486	2.805	1.258	2.588	2.675	0.594	5.628	5.911	1.828	4.995	5.593	2.583
14.000	2.502	2.570	0.601	2.487	2.805	1.257	2.588	2.674	0.593	5.631	5.913	1.829	4.996	5.593	2.585
15.000	2.502	2.571	0.602	2.488	2.806	1.258	2.590	2.673	0.592	5.633	5.916	1.829	4.996	5.593	2.587
16.000	2.503	2.571	0.603	2.487	2.806	1.260	2.592	2.674	0.592	5.634	5.917	1.828	4.997	5.594	2.590
17.000	2.504	2.572	0.603	2.486	2.805	1.263	2.594	2.674	0.594	5.634	5.917	1.826	4.996	5.594	2.593
18.000	2.504	2.572	0.604	2.485	2.803	1.265	2.596	2.675	0.594	5.631	5.916	1.823	4.995	5.595	2.596
19.000	2.503	2.572	0.604	2.484	2.801	1.265	2.597	2.676	0.593	5.629	5.914	1.821	4.994	5.595	2.599
20.000	2.501	2.571	0.605	2.483	2.800	1.263	2.597	2.677	0.592	5.627	5.911	1.821	4.993	5.594	2.599
21.000	2.500	2.571	0.607	2.482	2.799	1.259	2.596	2.676	0.590	5.628	5.910	1.821	4.993	5.593	2.598
22.000	2.499	2.572	0.609	2.482	2.799	1.254	2.593	2.673	0.589	5.630	5.910	1.822	4.993	5.592	2.595
23.000	2.499	2.572	0.611	2.482	2.800	1.250	2.590	2.670	0.589	5.632	5.911	1.823	4.992	5.592	2.593
24.000	2.499	2.573	0.611	2.482	2.802	1.248	2.587	2.668	0.589	5.633	5.912	1.823	4.993	5.592	2.591
25.000	2.501	2.574	0.609	2.482	2.803	1.250	2.583	2.666	0.590	5.632	5.912	1.824	4.993	5.592	2.590
26.000	2.502	2.575	0.607	2.483	2.805	1.253	2.581	2.666	0.591	5.629	5.913	1.824	4.993	5.592	2.589
27.000	2.503	2.575	0.605	2.483	2.806	1.255	2.581	2.667	0.592	5.627	5.913	1.823	4.992	5.590	2.588
28.000	2.503	2.575	0.602	2.484	2.805	1.254	2.583	2.667	0.594	5.626	5.914	1.823	4.991	5.588	2.586
29.000	2.502	2.573	0.600	2.484	2.803	1.250	2.586	2.668	0.596	5.626	5.913	1.824	4.990	5.586	2.585
30.000	2.499	2.571	0.600	2.485	2.801	1.245	2.591	2.670	0.597	5.626	5.911	1.825	4.990	5.585	2.583
31.000	2.497	2.570	0.600	2.486	2.799	1.241	2.594	2.671	0.598	5.625	5.910	1.827	4.990	5.586	2.583
32.000	2.495	2.569	0.600	2.486	2.798	1.239	2.595	2.672	0.598	5.624	5.910	1.829	4.991	5.587	2.583
33.000	2.494	2.569	0.600	2.486	2.798	1.237	2.593	2.671	0.598	5.623	5.911	1.830	4.992	5.588	2.584
34.000	2.495	2.569	0.601	2.486	2.798	1.236	2.590	2.668	0.597	5.624	5.912	1.831	4.993	5.590	2.586
35.000	2.497	2.570	0.602	2.486	2.798	1.235	2.587	2.666	0.597	5.626	5.913	1.831	4.993	5.591	2.588
36.000	2.500	2.570	0.602	2.486	2.800	1.237	2.584	2.666	0.596	5.629	5.914	1.831	4.993	5.592	2.591
37.000	2.502	2.571	0.603	2.487	2.801	1.241	2.583	2.666	0.595	5.631	5.914	1.831	4.992	5.593	2.594
38.000	2.504	2.571	0.602	2.488	2.802	1.249	2.584	2.669	0.595	5.633	5.914	1.832	4.991	5.594	2.597
39.000	2.504	2.571	0.601	2.489	2.803	1.257	2.584	2.672	0.596	5.634	5.914	1.833	4.991	5.594	2.599
40.000	2.504	2.570	0.600	2.489	2.803	1.262	2.584	2.673	0.597	5.635	5.914	1.834	4.992	5.594	2.596
41.000	2.504	2.570	0.602	2.488	2.802	1.263	2.583	2.672	0.597	5.635	5.914	1.835	4.993	5.594	2.591
42.000	2.503	2.570	0.605	2.486	2.802	1.260	2.580	2.668	0.597	5.635	5.913	1.835	4.993	5.593	2.585
43.000	2.502	2.570	0.608	2.485	2.801	1.255	2.578	2.665	0.596	5.634	5.912	1.834	4.994	5.592	2.581
44.000	2.502	2.570	0.610	2.484	2.801	1.252	2.575	2.663	0.596	5.632	5.911	1.832	4.995	5.591	2.578
45.000	2.502	2.570	0.609	2.484	2.801	1.249	2.572	2.664	0.595	5.629	5.910	1.829	4.996	5.592	2.578
46.000	2.502	2.570	0.606	2.484	2.800	1.245	2.569	2.667	0.596	5.628	5.909	1.827	4.998	5.593	2.580
47.000	2.502	2.569	0.603	2.485	2.799	1.240	2.571	2.670	0.597	5.628	5.909	1.826	4.999	5.594	2.582
48.000	2.501	2.570	0.601	2.487	2.800	1.239	2.580	2.667	0.598	5.630	5.910	1.829	4.999	5.594	2.581
49.000	2.500	2.570	0.601	2.490	2.803	1.247	2.601	2.656	0.600	5.634	5.909	1.836	4.995	5.589	2.572
50.000	2.501	2.573	0.604	2.493	2.801	1.242	2.581	2.663	0.597	5.630	5.913	1.833	4.999	5.595	2.581
Mean	2.500	2.570	0.604	2.485	2.803	1.255	2.588	2.672	0.595	5.630	5.913	1.828	4.994	5.592	2.589
SD	0.004	0.002	0.003	0.003	0.003	0.012	0.007	0.006	0.003	0.004	0.002	0.004	0.002	0.003	0.007
Actual	2.500	2.571	0.600	2.500	2.795	1.250	2.500	2.571	0.600	5.590	5.873	1.800	5.000	5.590	2.500
Variation	0.000	0.001	-0.004	0.015	-0.008	-0.005	-0.088	-0.101	0.005	-0.040	-0.040	-0.028	0.006	-0.002	-0.089
%error	0.008	0.022	-0.623	0.610	-0.275	-0.427	-3.517	-3.911	0.833	-0.723	-0.673	-1.572	0.124	-0.027	-3.547

Appendix F:

Calibration Frame Accuracy for Individual Subject

Table J.1. Calibration frame accuracy for individual subjects.

		X	Y	Z	Resultant
1	Ave. Mean Sq. Error	0.006	0.009	0.010	0.015
	Ave. Vol. % error	0.116	0.493	0.425	0.256
2	Ave. Mean Sq. Error	0.006	0.008	0.009	0.014
	Ave. Vol. % error	0.121	0.465	0.366	0.235
3	Ave. Mean Sq. Error	0.007	0.014	0.017	0.023
	Ave. Vol. % error	0.142	0.769	0.688	0.395
4	Ave. Mean Sq. Error	0.010	0.010	0.018	0.021
	Ave. Vol. % error	0.084	0.539	0.741	0.363
5	Ave. Mean Sq. Error	0.004	0.010	0.018	0.021
	Ave. Vol. % error	0.084	0.539	0.741	0.363
6	Ave. Mean Sq. Error	0.007	0.010	0.018	0.022
	Ave. Vol. % error	0.138	0.557	0.741	0.377
7	Ave. Mean Sq. Error	0.007	0.010	0.018	0.022
	Ave. Vol. % error	0.138	0.557	0.741	0.377
8	Ave. Mean Sq. Error	0.005	0.008	0.015	0.018
	Ave. Vol. % error	0.096	0.430	0.614	0.304